Hao ZHANG, Bin XIN, Li-hua DOU, Jie CHEN, Kaoru HIROTA, 2020. A review of cooperative path planning of an unmanned aerial vehicle group. *Frontiers of Information Technology & Electronic Engineering,* 21(12):1671-1694. https://doi.org/10.1631/FITEE.2000228

A review of cooperative path planning of an unmanned aerial vehicle group

Key words: Unmanned aerial vehicle group; Cooperation; Path planning; Optimization problem

Corresponding author: Bin XIN
E-mail: brucebin@bit.edu.cn
ORCID: https://orcid.org/0000-0001-9989-0418

Motivation

1. Because tasks faced by UAVs are increasingly complex, a single UAV is usually not capable of performing extensive tasks, such as express transportation, disaster relief, surveying and mapping, and power-line inspection.
2. As a cutting-edge branch of unmanned aerial vehicle (UAV) technology, the cooperation of a group of UAVs has attracted increasing attention from both civil and military sectors, due to its remarkable merits in functionality and flexibility for accomplishing complex extensive tasks.
3. In this paper, more attention is paid to the review of cooperative path planning problems from the perspective of optimization, and more focus is on the analysis and classification of cooperative path planning problems.

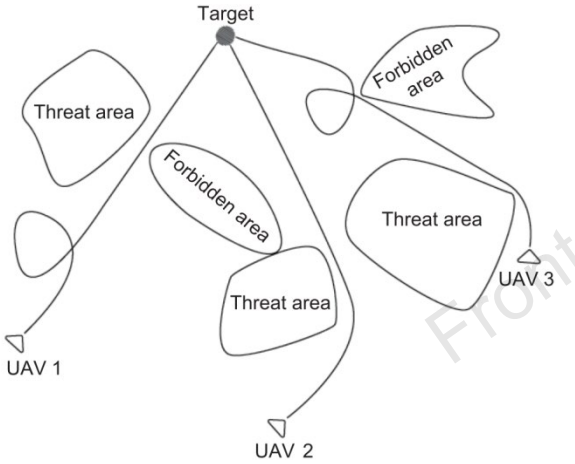
Main idea

1. A generalized framework of cooperative path planning problems and a taxonomy are developed to allow different problems to be described in a unified way, and an optimization perspective is provided to analyze and classify the existing research.
2. A review and a statistical analysis are presented based on the taxonomy, emphasizing the coordinative elements in the existing cooperative path planning research.
3. A collection of challenging cooperative path planning problems are provided to highlight future research directions.

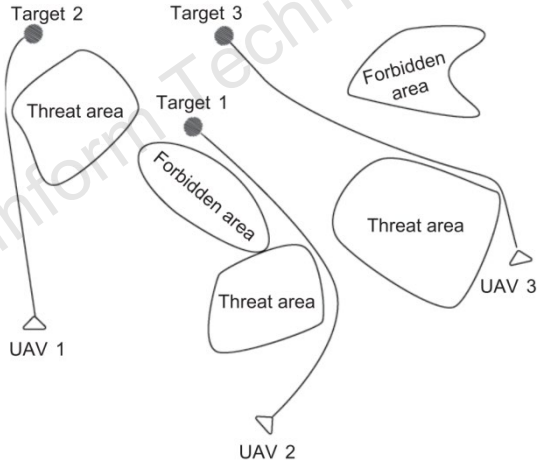
Key elements of cooperative path planning

1. Tasks

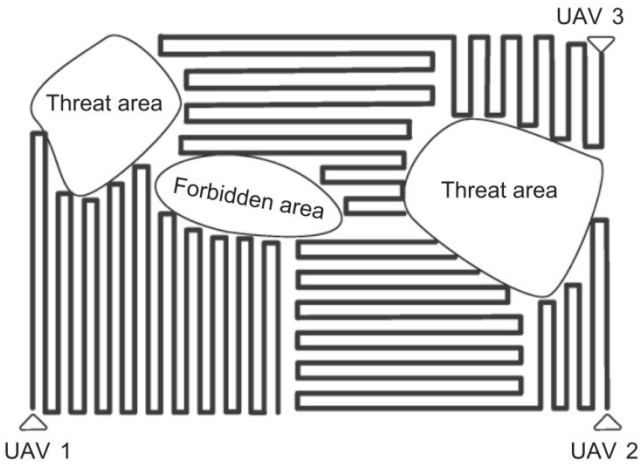
Due to the diversity of tasks, cooperative path planning problems take many forms. The tasks can be generally divided into three categories: rendezvous, allocation, and coverage tasks.



Rendezvous task



Allocation task



Coverage task

Key elements of cooperative path planning

2. UAV group

The following attributes of the CPP executor, i.e., the UAV group, must be considered.

- **Organizational framework:** centralized, decentralized, and hybrid frameworks
- **Spatial relationship:** aggregated and dispersed cases
- **UAV type:** fixed- and rotary-wing

UAV type	Advantages	Disadvantage	Flight path
Fixed-wing UAV	High speed, large scope of observation, strong communication ability	Low observation accuracy	Smooth curve
Rotary-wing UAV	Vertical takeoff and landing, hovering ability, precise inspection	Low payload capability	Polyline or smooth curve

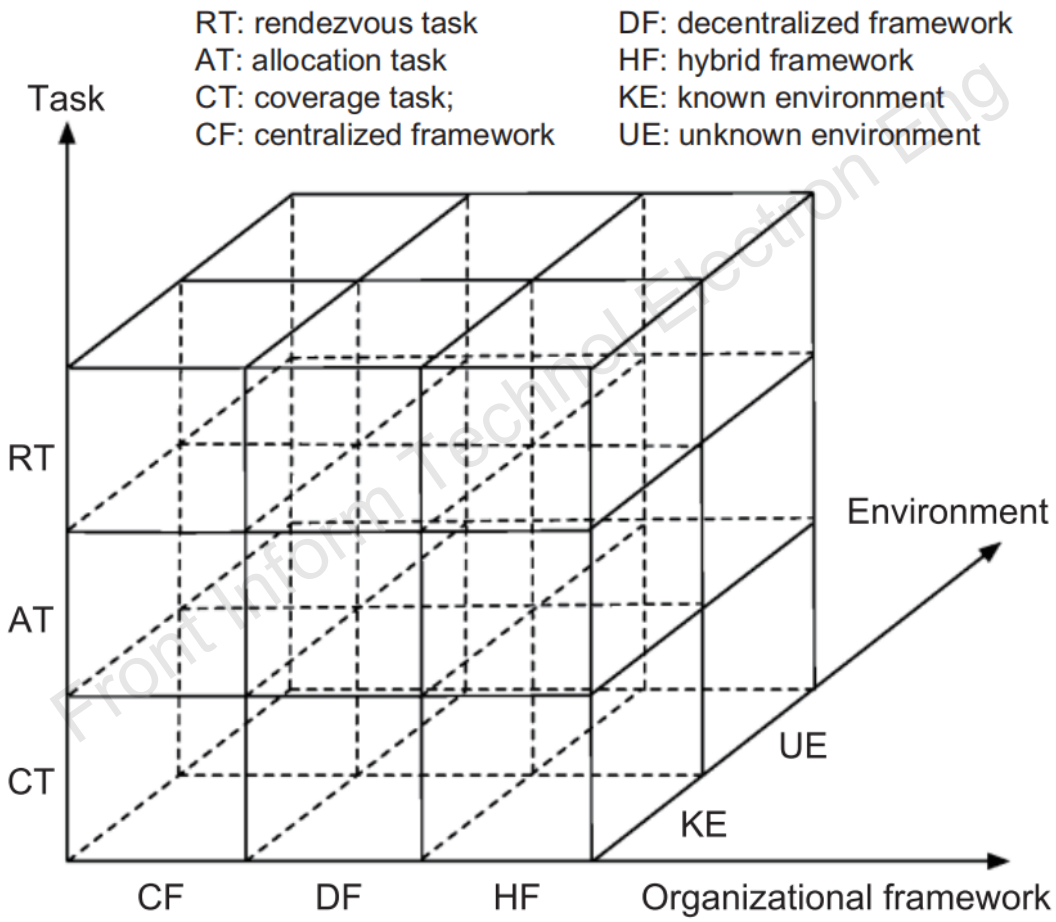
Key elements of cooperative path planning

3. Environment

Environmental diversity creates challenges in the CPP problems, mainly in the areas of dimension, uncertainty, and complexity.

- **Dimension:** two-dimensional (2D) and three dimensional (3D) environments.
- **Uncertainty:** There may be unpredictable dynamic factors in the environment, such as an intruder aircraft (IA) with unknown trajectories and pop-up threads.
- **Complexity:** The air through which UAVs move can be regarded as a medium, and many factors cause changes in the medium. In addition, the environment may show different complexities and features in different task scenarios.

Taxonomy of cooperative path planning



- **Taxonomy:** Three elements, including the task, organizational framework, and environment, are considered.

Review of cooperative path planning based on the taxonomy

Reference	Classification	Environment	UAVs	1	2	3	4	5	6
Chen YB et al. (2016)	RT-CF-KE	3D, battlefield	=	–	–	–	–	√	–
Huang et al. (2016)	RT-CF-KE	2D, battlefield	=	–	–	–	–	√	–
Yang XX et al. (2016)	RT-CF-KE	2D, obstacle-free	=	–	–	–	–	√	√
Sun JY et al. (2017)	RT-CF-KE	3D, urban	=	–	√	–	–	–	–
Shao et al. (2019)	RT-CF-KE	3D, obstacle	=	–	√	–	–	√	–
Liu Y et al. (2019)	RT-CF-KE	3D, battlefield	=	–	√	–	–	√	–
Chen QY et al. (2018)	RT-CF-KE	2D, obstacle-free	=	–	√	–	√	√	–
Wang et al. (2017)	RT-CF-KE	2D, obstacle	=	–	√	–	√	√	–
Zhang DF and Duan (2018)	RT-CF-KE	3D, battlefield	=	–	√	√	√	–	–
Radmanesh et al. (2018a)	RT-CF-UE	2D, civilian airspace	=	√	√	–	–	√	–
Falomir et al. (2018)	RT-DF-KE	2D, urban	=	–	√	–	–	–	–
Chen YB et al. (2015)	RT-DF-KE	3D, battlefield	=	–	√	–	√	–	–
Liu W et al. (2013)	RT-DF-KE	2D, battlefield	≃	–	√	√	–	–	–
Zhang QJ et al. (2015)	RT-DF-UE	2D, battlefield	=	√	–	–	–	√	–
Ma PB et al. (2014)	RT-DF-UE	2D, battlefield	=	√	–	–	–	√	–

RT: rendezvous task; CF: centralized framework; DF: decentralized framework; KE: known environment; UE: unknown environment. 1: real time; 2: collision avoidance among UAVs; 3: connectivity; 4: formation; 5: synchronicity; 6: heading coordination. =: homogeneous; ≃: heterogeneous; √: considered; –: not considered

Review of cooperative path planning based on the taxonomy

Reference	Classification	Environment	UAVs	1	2	3	4	5	6
Wang et al. (2019)	AT-CF-KE	2D, obstacle	=	–	√	–	–	√	–
Shi et al. (2017)	AT-CF-KE	2D, battlefield	=	–	–	–	–	–	–
Dewangan et al. (2019)	AT-CF-KE	3D, obstacle	=	–	√	–	–	–	–
Babel (2019)	AT-CF-KE	2D, obstacle	=	–	√	–	–	√	√
Wu JY et al. (2017)	AT-CF-KE	3D, battlefield	=	–	√	–	–	–	–
Ergezer and Leblebicioğlu (2014)	AT-CF-KE	3D, mountain	=	–	–	–	–	–	–
Çakıcı et al. (2016)	AT-CF-KE	3D, mountain	=	–	–	–	–	–	–
Sahingoz (2013, 2014)	AT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Cekmez et al. (2016)	AT-CF-KE	2D, battlefield	=	–	–	–	–	–	–
Li XH et al. (2016)	AT-CF-KE	2D, farmland	=	–	–	–	–	–	–
Li T et al. (2016)	AT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Manyam et al. (2017)	AT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Sørli et al. (2017)	AT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Harounabadi et al. (2018)	AT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Binol et al. (2018)	AT-CF-KE	2D, road network	=	–	–	–	–	–	–
Ning et al. (2019)	AT-CF-KE	2D, battlefield	=	–	–	–	–	–	–
Cho et al. (2019)	AT-CF-KE	2D, obstacle-free	≃	–	–	–	–	–	–
Zhao M et al. (2017)	AT-CF-KE	3D, battlefield	=	–	–	–	–	√	–
Zhang X et al. (2014)	AT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Qin et al. (2018)	AT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Yang J et al. (2018)	AT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Quintin et al. (2017)	AT-CF-KE	2D, obstacle	≃	–	–	–	–	–	–
Zhao Z et al. (2019)	AT-CF-KE	3D, obstacle	=	√	–	–	–	–	–
Su et al. (2016)	AT-CF-UE	3D, battlefield	=	√	√	–	–	–	–
Ma XB et al. (2016, 2018)	AT-DF-KE	3D, urban-like	=	–	√	–	–	–	–
Causa et al. (2018)	AT-DF-KE	3D, urban	=	–	–	–	–	√	–
Chen X et al. (2017)	AT-DF-KE	2D, battlefield	=	–	–	–	–	√	–
Ghamry et al. (2017)	AT-DF-KE	2D, obstacle-free	=	–	√	–	–	–	–
Yao WR et al. (2019)	AT-DF-KE	2D, urban	=	–	–	–	–	–	–
Yoon et al. (2017)	AT-DF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Sun XL et al. (2015)	AT-DF-UE	3D, obstacle	=	√	–	–	–	–	–
Kothari et al. (2009)	AT-DF-UE	2D, obstacle-rich	=	√	√	–	–	–	–
Wu ZY et al. (2018)	AT-DF-UE	2D, obstacle	=	√	√	–	–	–	–
Moon et al. (2013)	AT-DF-UE	3D, obstacle	=	√	√	–	–	–	–
Yao WR et al. (2016)	AT-DF-UE	2D, obstacle	=	√	–	–	–	–	–
Jang et al. (2019)	AT-DF-UE	2D, obstacle	≃	√	√	–	–	–	–
Yang et al. (2019a, 2019b)	AT-HF-KE	2D, obstacle	≃	√	–	–	–	√	–

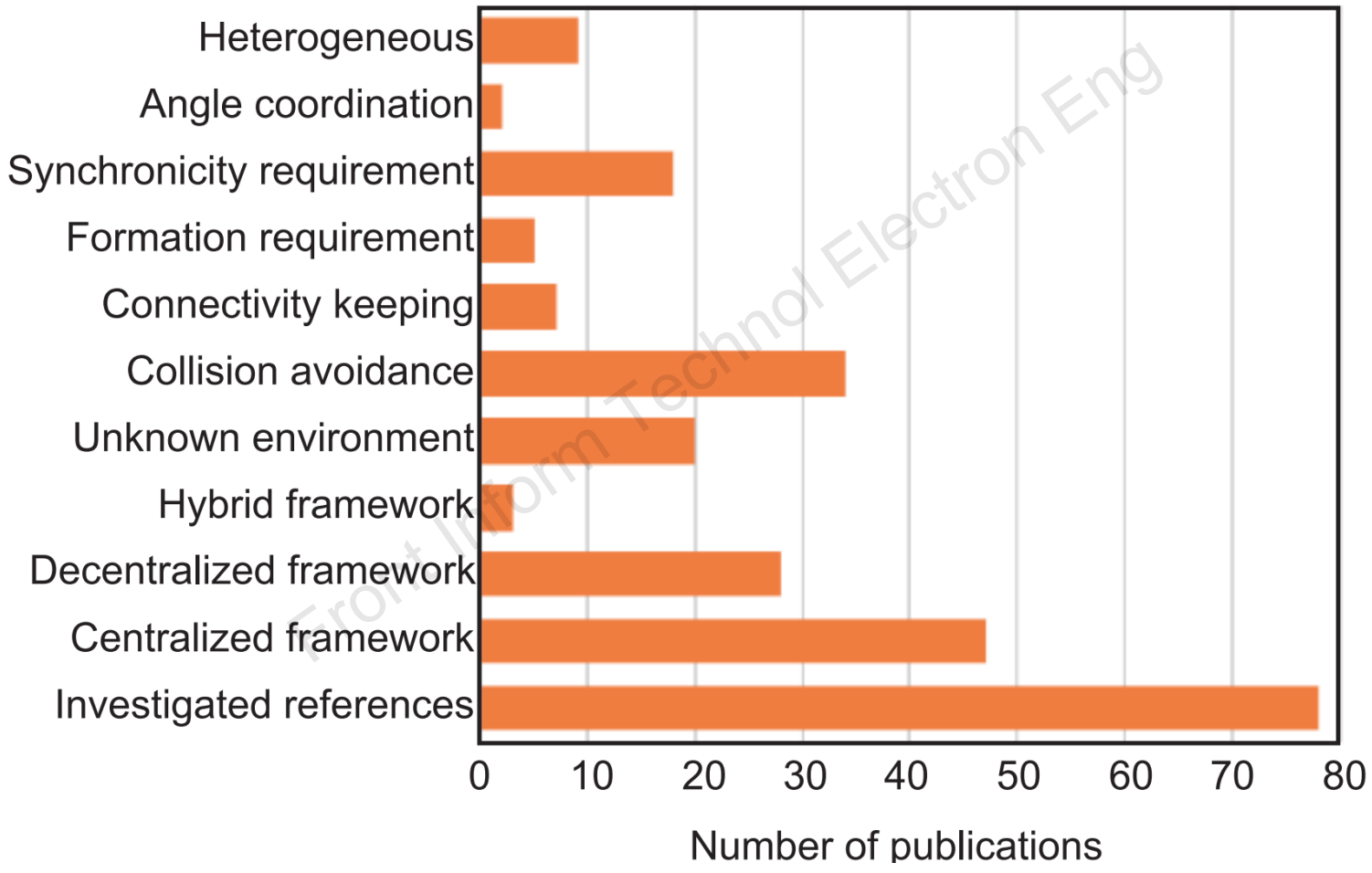
AT: allocation task; CF: centralized framework; DF: decentralized framework; HF: hybrid framework; KE: known environment; UE: unknown environment. 1: real time; 2: collision avoidance among UAVs; 3: connectivity; 4: formation; 5: synchronicity; 6: heading coordination. =: homogeneous; ≃: heterogeneous; √: considered; –: not considered

Review of cooperative path planning based on the taxonomy

Reference	Classification	Environment	UAVs	1	2	3	4	5	6
Lin et al. (2018)	CT-CF-KE	3D, mountain	=	–	√	–	–	–	–
Li JD et al. (2018)	CT-CF-KE	3D, plateau and mountain	=	–	–	–	–	–	–
Mansouri et al. (2018)	CT-CF-KE	3D, urban	=	–	√	–	–	–	–
Maza and Ollero (2007)	CT-CF-KE	2D, obstacle-free	≃	–	–	–	–	–	–
Bouzid et al. (2019)	CT-CF-KE	2D, obstacle	=	–	√	–	–	–	–
Avellar et al. (2015)	CT-CF-KE	2D, obstacle-free	=	–	–	–	–	–	–
Zheng et al. (2018)	CT-CF-KE	3D, urban	=	–	√	–	–	–	–
Govindaraju et al. (2014)	CT-CF-KE	2D, forest	=	–	–	–	–	–	–
Yao P et al. (2017)	CT-CF-KE	3D, urban	=	–	√	–	–	√	–
Balampanis et al. (2017)	CT-CF-KE	2D, coastland	≃	–	√	–	–	–	–
Hoang et al. (2018)	CT-CF-KE	3D, urban	=	–	√	–	√	–	–
Lazarus et al. (2010)	CT-CF-UE	2D, obstacle	=	√	√	–	–	–	–
Luo et al. (2019)	CT-CF-UE	2D, obstacle	=	√	√	–	–	–	–
Yang F et al. (2017)	CT-CF-UE	2D, obstacle-free	=	√	–	–	–	–	–
Gupta et al. (2017)	CT-DF-KE	2D, obstacle	=	–	–	–	–	–	–
Ji et al. (2015)	CT-DF-KE	2D, obstacle	=	–	–	√	–	–	–
Park et al. (2018)	CT-DF-KE	2D, obstacle-free	=	–	–	√	–	–	–
Yao P et al. (2018)	CT-DF-KE	2D, ocean	=	√	–	–	–	–	–
Azpùrua et al. (2018)	CT-DF-KE	2D, plain	=	–	–	√	–	–	–
Chen J et al. (2013)	CT-DF-UE	2D, battlefield	≃	√	√	√	–	–	–
Zhen et al. (2018)	CT-DF-UE	2D, battlefield	≃	√	√	–	–	–	–
Wu QP et al. (2014)	CT-DF-UE	2D, obstacle-free	=	√	√	–	–	–	–
Liu Z et al. (2018)	CT-DF-UE	2D, obstacle-free	=	√	√	√	–	–	–
Hu et al. (2017)	CT-DF-UE	2D, obstacle-free	=	√	–	–	–	–	–
Yang YL et al. (2007)	CT-DF-UE	2D, obstacle-free	=	√	–	–	–	–	–
Long and Zhu (2011)	CT-HF-UE	2D, obstacle	=	√	–	–	–	–	–

CT: coverage task; CF: centralized framework; DF: decentralized framework; HF: hybrid framework; KE: known environment; UE: unknown environment. 1: real time; 2: collision avoidance among UAVs; 3: connectivity; 4: formation; 5: synchronicity; 6: heading coordination. =: homogeneous; ≃: heterogeneous; √: considered; –: not considered

Review of cooperative path planning based on the taxonomy



Statistics of key issues in the literature in Web of Science from 2007 to 2019

Future research directions

- Cooperative path planning for a large-scale UAV swarm
- Cooperative path planning in the cooperation of heterogeneous vehicles
- Cooperative path planning in swarm-versus-swarm UAV games
- Cooperative path planning with variable communication topology
- Cooperative path planning in complex mixed environments

Conclusions

- This review provides a systematic overview of the current research on cooperative UAV group path planning by focusing on the three elements of the system (i.e., task, UAV group, and environment) and the three elements of the cooperative path planning problem (i.e., UAV paths, constraints, and objectives).
- A taxonomy of various cooperative path planning problems has been proposed and used as clues to classify the existing research and identify their features.
- A comparative statistical analysis regarding various issues in cooperative path planning reveals some shortcomings and gaps in current research.
- A collection of challenging cooperative path planning problems and interesting topics have been presented for future research.