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# A survey of the pursuit–evasion problem in swarm intelligence



**Key words:** Swarm behavior; Pursuit–evasion; Artificial systems; Biological model; Collective motion

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# Introduction

A novel taxonomy and comprehensive survey of swarm intelligence from the perspective of the pursuit–evasion problem:

- We review the problem of pursuit–evasion from three different perspectives: game theory, control theory and artificial intelligence, and bio-inspired perspectives.
- We establish a link between the pursuit–evasion problem and collective motion, and provide an overview of the research on pursuit–evasion problems in biological systems and artificial systems.
- We analyze the applications of pursuit–evasion in artificial systems from three perspectives based on the ability of pursuers and evaders.
- We discuss relevant prospects for future pursuit–evasion challenges.

# Pursuit–evasion problem

- The pursuit–evasion problem originated from collective behavior research. The goal is to model and solve the confrontation between pursuers and evaders, which focuses on the strategies of two groups: pursuers try to capture evaders and evaders try to escape from the pursuers.

- The pursuit–evasion problem as a general framework is widely applied in different scenarios, such as confrontation in the military field, surveillance, and analysis of biological behaviors.

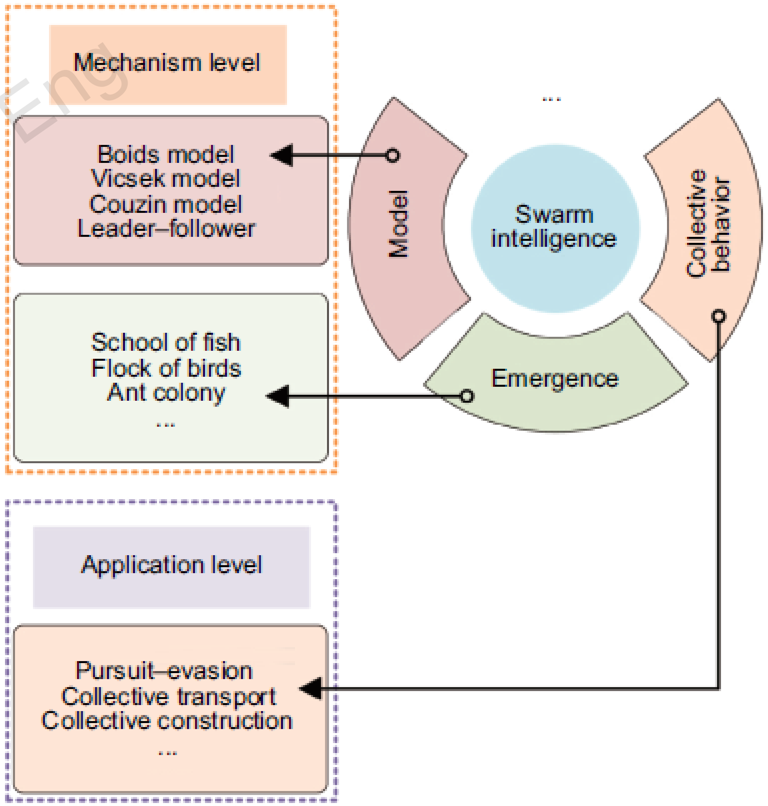


**Fig. 1** The taxonomy based on the swarm intelligence research level

# Pursuit–evasion problem

- Many classical and attractive problems have been derived from the pursuit–evasion game, with these variations studied from various perspectives.
- Those variations of pursuit–evasion games have highlighted the insight of the optimal strategy solution and expanded their application scenarios.

**Table 1 Variations of the pursuit–evasion game**

| Variation | Characteristic | Application scenario |
|---|---|---|
| Homicidal chauffeur problem (Isaacs, 1999) | Pursuer is faster than evader; the turning radius of the pursuer is limited, while that of the evader is unlimited | This reflects the animal predation process in reality, where a fast but inflexible predator chases slow but agile prey. It is also applied to military scenarios such as missile interception, missile defense, and anti-terrorism |
| Game of two cars (Merz, 1972) | Pursuer and evader have the same speed and turning radius | Because both the pursuer and the evader have exactly the same attributes, there are some prerequisites for their initial positions and distances. This scenario is rarely encountered in real applications |
| Two cutters and fugitive ship game (Garcia et al., 2017) | Two pursuers are faster than one evader. Two cooperative pursuers attempt to capture the slower evader in the minimum time | As described in the game, two patrol ships cooperate to intercept escaping enemy ships |
| Guarding a territory (Analikwu and Schwartz, 2017) | The invader aims to avoid capture and tries to reach the territory, while the guard attempts to intercept the invader far away from the territory | In military applications, the guard protects the territory's critical infrastructure from physical attacks. The application in policing is protecting borders against illegal entries and other dangerous activities |
| Active target defense differential game (Garcia et al., 2018) | The defender and target cooperate in an effort to protect the actively maneuvering target from the attacker's capture, while the defender aims to intercept the attacker | In military confrontation applications, intercepting offensive missiles by launching defensive missiles protects the target aircraft from threats and attacks |
| Fish game (Zha et al., 2017) | The faster evader attempts to pass the gap between two pursuers while avoiding the pursuit of the two pursuers, with a capture radius of zero | The robot passes through the gap between two moving obstacles and avoids collisions. In military confrontation, two missiles attempt to intercept an enemy target |
| Reach-avoid game (Yan R et al., 2019) | Two defenders try to intercept an attacker before the attacker reaches the target line | This application scenario has an additional goal line compared to the fish game. In military confrontation, two frigates guard the coastline against enemy ships |

# Framework

Main methods

- Game theory
- Control theory & artificial intelligence
- Bio-inspired

Novel taxonomy

- Strong vs. weak
- Weak vs. strong
- Equal ability

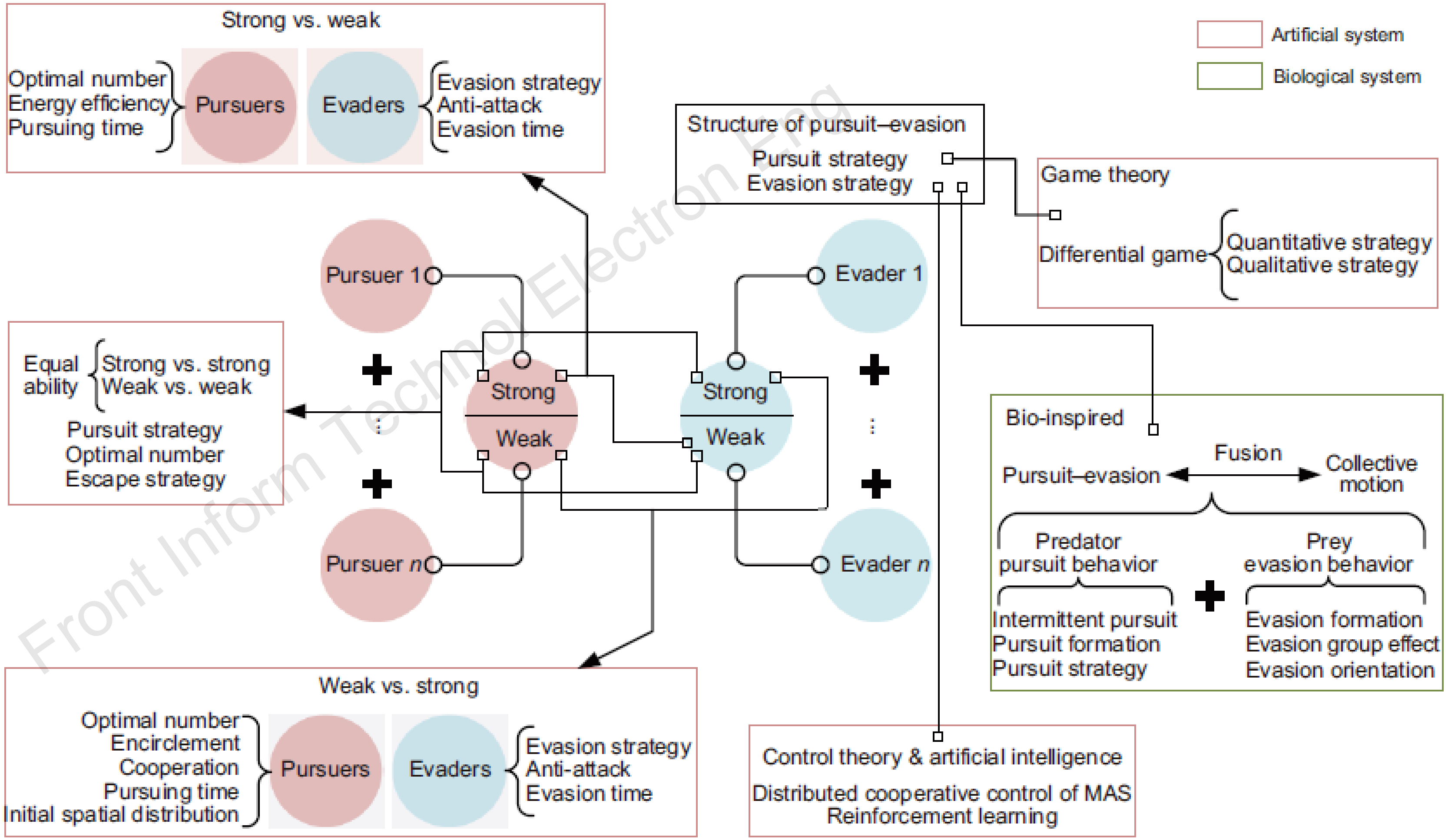


**Fig. 2 Framework of the pursuit–evasion problem**

# Basic model

**Table 2 Comparison of various model characteristics**

| Model | Characteristic |
|---|---|
| Boids model (Reynolds, 1987) | Three basic principles: separation, alignment, and cohesion |
| Vicsek model (Vicsek et al., 1995) | The model is based on particle collective motion, considering only velocity synchronization |
| Couzin model (Couzin et al., 2002) | The perceptual range is divided into three areas, the blind area of the visual field is considered, and the turning angle is added |
| Leader–follower (Jadbabaie et al., 2003; Couzin et al., 2005) | Within the swarm, there are two types of roles: leader and follower. The leader has a fixed heading, and the movements of all individuals in the system will eventually converge to the leader |

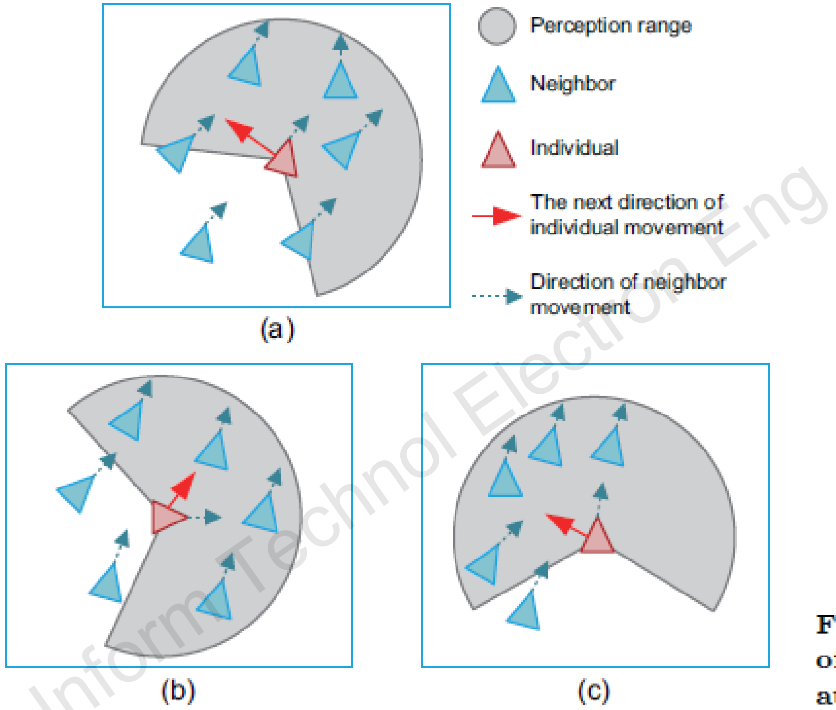


**Fig. 3 Illustration of Boids model: (a) separation; (b) alignment; (c) cohesion**

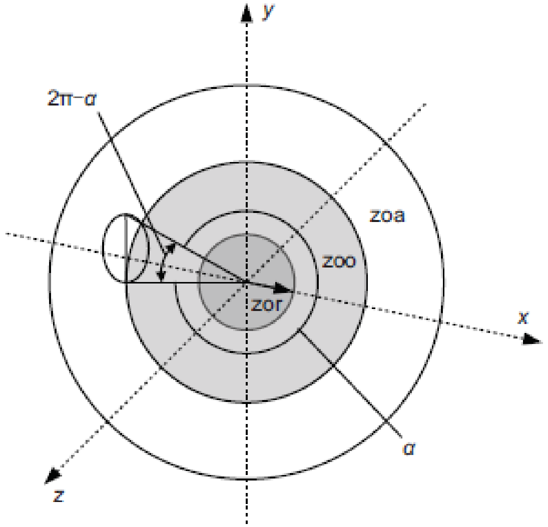


**Fig. 4 Illustration of the Couzin model (zor: zone of repulsion; zoo: zone of orientation; zoa: zone of attraction)**

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- The swarm model is used mainly to imitate the collective biological behavior in multi-agent system (MAS) and multi-robot system (MRS).
- The motivation for studying the swarm model is to understand the intrinsic mechanism of emergence, which is significant for designing artificial systems.

# Comparison of methods

- Common characteristics
  - Same goal. The pursuer tries to find and capture the evader, while the evader avoids being caught.
  - Constraints. Both sides of the pursuit–evasion game have certain constraints in real situations.
  - Equilibrium. The abilities of the pursuer and the evader are studied under the premise of trade-offs.

- Differences
  - Game theory focuses on differential games, and suits the relatively simple mathematical game model.
  - Control theory and artificial intelligence are more suitable for large-scale, more complex nonlinear pursuit–evasion processes.
  - Bio-inspired focuses on the local rules of individuals, and by imitating the tasks and roles of biological swarm individuals in the group, complex global behaviors emerge.

# Biological system & artificial system

- Predator pursuit behavior
  - Intermittent pursuit
  - Pursuit formation
  - Classic pursuit and CATD pursuit
- Prey evasion behavior
  - Evasion formation
    - Ball
    - Flash expansion
  - Evasion group effect
    - Dilution effect
    - Confusion effect
    - Marginal predation
  - Evasion orientation
- Strong pursuer group vs. weak evader group
  - Escape strategy of the weak evader
  - The optimal number of pursuers for the strong pursuer
- Weak pursuer group vs. strong evader group
  - Cooperative strategy of the pursuer
  - The optimal number of the weak pursuers
  - Initial spatial distribution around the evader
- Equal-ability pursuit–evasion
  - Differential game methods to find the capture zone and escape zone in strategy space

# Future studies

- Emergence mechanism and quantitative metrics
- Heterogeneous system design
- Generalization of strategy
- Uncertain pursuit speed
- Environment feature prediction
- Cyber security

# Conclusions

1. We reviewed the classical pursuit–evasion models and then discussed the pursuit–evasion problem from the perspectives of biological systems and artificial systems.

2. We proposed a taxonomy of swarm behavior according to the characteristics of the swarm system and introduced swarm behavior in biological systems and artificial systems.

3. We discussed the applications of relevant pursuing strategies from three perspectives: strong pursuer group vs. weak evader group, weak pursuer group vs. strong evader group, and equal-ability group.

4. We discussed some key problems and future studies to promote the development and improvement of pursuit–evasion in swarm intelligence.

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