Chinese Journal of Aeronautics, (2016), 29(6): 1709–1720

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Distributed online mission planning for multi-player space pursuit and evasion

Liu Yuan [a], **Ye Dong** [b,*], **Hao Yong** [a]

[a] *College of Automation, Harbin Engineering University, Harbin 150001, China*
[b] *Research Center of Satellite Technology, Harbin Institute of Technology, Harbin 150001, China*

Received 24 September 2015; revised 8 November 2015; accepted 18 May 2016
Available online 21 October 2016

KEYWORDS

Evaluation;
Nash equilibrium solution;
Pursuit-evasion strategy;
Planning;
Space

Abstract There are three important roles in evasion conflict: pursuer, target and defender. Pursuers' mission is to access targets; targets' mission is to escape from pursuers' capture; defenders' mission is to intercept pursuers who are potentially dangerous to targets. In this paper, a distributed online mission plan (DOMP) algorithm for pursuers is proposed based on fuzzy evaluation and Nash equilibrium. First, an integrated effectiveness evaluation model is given. Then, the details of collaborative mission planning which includes the co-optimization of task distributing, trajectory and corresponding maneuvering scheme are presented. Finally, the convergence and steadiness of DOMP are discussed with simulation results. Compared with centralized mission planning, DOMP is more robust and can greatly improve the effectiveness of pursuing. It can be applied to dynamic scenario due to its distributed architecture.

1. Introduction

In addition to the standard pursuit-evasion game, in which the pursuer tries to catch the target and the target tries to escape, the defender intercepts pursuer to protect target. This conflict has attracted increasing attention in space technology research.[1] As one type of low-cost spacecraft, small satellites with characteristics of lightness, agility, large coverage, etc. have become the ideal pursuer in the study of pursuit-evasion conflict.[2–4] Some representative projects are US AFRL's (Air Force Research Laboratory) XSS (Experimental Satellite System), DARPA's (Defense Advanced Research Project Agency), MiTEx (Mirco-satellite Technology Experiment) and NASA's DART (Demonstration for Autonomous Rendezvous Technology).[3–5]

To successfully access targets, pursuers must survive from defenders' interception.[6] Facing multiple targets and multiple defenders, pursuers must cooperate to obtain the optimal pursuing effectiveness.[7–11] Therefore, collaborative mission planning is important for pursuers.

For a multi-agent system, a joint strategy is a set of individual policies with one for each agent. An optimal strategy can maximize the expected gains of the system. The process of

* Corresponding author. Tel.: +86 451 86412357.
E-mail addresses: undertwilight@foxmail.com (Y. Liu), yed@hit.edu.cn (D. Ye), haoyong@hrbeu.edu.cn (Y. Hao).

Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.10.012
1000-9361

obtaining the optimal strategy is called mission planning, which is an NP-hard problem. Generally, there are two types of mission planning: centralized and distributed. Typically, a centralized planning system consists of one leader and several followers, where the leader is a unique planner of the system. Because multi-agent models and the planning algorithm lead to huge state spaces, the leader needs to have significant computational resources. Once it is damaged, the whole system would crash. On the other hand, mission planning could run on each agent as well, in which case every agent has the same priority. Therefore, one or a few of agents' failure would not affect the whole system's operation. In a distributed planning system, each agent calculates its own policy while other agents' policies are considered fixed, and broadcasts their planning results to others. Since any modification of an agent's policy might induce other agents' reward change, agents iteratively update their policies until a system equilibrium is reached. Compared with centralized planning, distributed planning has advantages of autonomous agents, robust system and real time.[12] Hence, distributed planning is more applicable in a high dynamic antagonistic application, such as space pursuit and evasion. In the past few years, popular approaches for multi-agent mission planning are contract net protocol, visibility graph and heuristic algorithms such as genetic algorithm (GA).[13,14]

In a space pursuit and evasion conflict, pursuers' mission planning is a complex problem, which is affected by many factors such as high relative speed, strict fuel limitation, real-time requirement. Besides, the intercepting role of defenders further increases the complexity of pursuers' planning, which creates constraints on well-developed algorithm such as visibility graph. Therefore, previous works mainly focus on the optimization and modeling of single pursuer's trajectory.[15,16] Multi-player space pursuit and evasion problem still lacks a thorough and systematic study. In this paper, a distributed online mission plan (DOMP) algorithm for multi-player pursuers is presented, and the dynamics used in this algorithm is explained. Then a multi-objective effectiveness model is used to quantitatively estimate policies. After a set of potential pursuing trajectories is obtained by fuzzy comprehensive evaluation, pursuers can reach the Nash equilibrium point through local optimization, negotiation and iteratively updating information about neighbors. Finally, a simulation example demonstrates the effectiveness of DOMP algorithm.

2. Problem description

2.1. Space pursuit and evasion conflict

Normally, to reduce energy consuming and prolong on-orbit life, small satellites that perform as pursuers work in standby mode, in which the satellites only make periodic self-inspection and necessary orbit maintenance. Once they receive wake-up command, they will go into preparation mode and try to approach targets.

The basic concept of space pursuit and evasion conflict is shown in Fig. 1. It includes a cluster of pursuers. In the intensive space pursuit and evasion scenario, we assume that there are multiple targets. Hence, cooperative pursuing trajectory optimization and target assigning are two critical factors in mission planning.

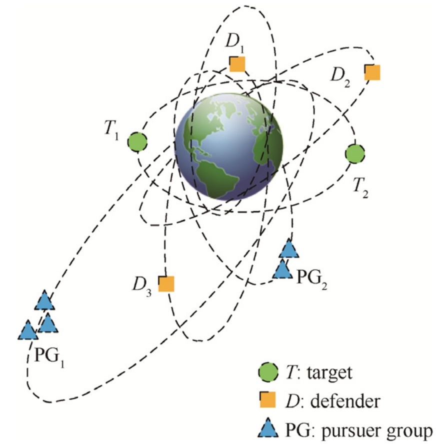

Fig. 1 Basic conception of space pursuit and evasion.

2.2. Integral effectiveness model

Mission planning algorithm produces an optimal pursuing strategy for pursuers. It is evaluated by the integral pursuing effectiveness, which includes various factors, such as benefit, expending and capture probability. The evaluation of pursuing strategy is affected by the situation (objective) and the preference (subjective). Overall, a mathematical multi-objective effectiveness model for pursuing strategy can be expressed as Eq. (1).

$$\begin{aligned} &\max \ E = f_{\mathrm{e}}(\boldsymbol{\lambda}, \boldsymbol{O}(k_{\mathrm{m}})) \\ &\text{s.t.} \begin{cases} \boldsymbol{O}(k_{\mathrm{m}}) = f_{\mathrm{o}}(\boldsymbol{S}(k_{\mathrm{m}}), \boldsymbol{D}(k_{\mathrm{m}}), \boldsymbol{A}(k_{\mathrm{m}})) \\ \boldsymbol{S}(k_{\mathrm{m}}+1) = f_{\mathrm{s}}(\boldsymbol{S}(k_{\mathrm{m}}), \boldsymbol{D}(k_{\mathrm{m}})) \\ \sum_{i=1}^{m} \lambda_i = 1, \boldsymbol{\lambda} = [\lambda_1, \lambda_2, \ldots, \lambda_m] \\ r_{ij}(k_{\mathrm{m}}) \leqslant R_{ij}(k_{\mathrm{m}}) \quad (i = 1, 2, \ldots, n; j = 1, 2, \ldots, l) \\ \boldsymbol{S}(k_{\mathrm{m}}) \subseteq \boldsymbol{S}_{\mathrm{s}}, \boldsymbol{D} \subseteq \boldsymbol{D}_{\mathrm{d}} \end{cases} \end{aligned} \tag{1}$$

where $\boldsymbol{O}(k_{\mathrm{m}}) = [O_1, O_2, \ldots, O_m]$ is the current objective vector; m is the number of sub-objectives; k_{m} is the time of current moment; $\boldsymbol{\lambda}$ is the normalized subjective weight vector with the proper dimension; E is the effectiveness; $\boldsymbol{S}$ and $\boldsymbol{A}$ are the state vectors of pursuers and targets respectively; $\boldsymbol{D}$ is the strategy vector of the pursuers; f_{e} is the effectiveness function representing the integral effectiveness according to the current strategy and the current situation; f_{o} is the objective function describing the mapping from state space to objective space; f_{s} is the state transferring function; $\boldsymbol{S}_{\mathrm{s}}$ and $\boldsymbol{D}_{\mathrm{d}}$ identify the state space and decision space respectively; $r_{ij}(k_{\mathrm{m}})$ indicates the consumption of the jth resource when pursuer i executes current strategy; and $R_{ij}(k_{\mathrm{m}})$ represents the amount of the jth resource of pursuer i.

The essence of space pursuit and evasion mission planning is an optimization process with comprehensive constraints. The global optimal solution cannot always be acquired in limited time under the greatly varying circumstances (even if we obtain a global optimal solution with much time, it may be meaningless). Therefore, the key solution to mission planning is to achieve a series of sub-optimal strategies in limited time, and then select an optimal one which can best satisfy the mission's requirements with the highest effectiveness.