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Mission decision-making method of multi-aircraft cooperatively attacking multi-target based on game theoretic framework

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Situational assessment

Abstract Coordinated mission decision-making is one of the core steps to effectively exploit the capabilities of cooperative attack of multiple aircrafts. However, the situational assessment is an essential base to realize the mission decision-making. Therefore, in this paper, we develop a mission decision-making method of multi-aircraft cooperatively attacking multi-target based on situational assessment. We have studied the situational assessment mathematical model based on the Dempster-Shafer (D-S) evidence theory and the mission decision-making mathematical model based on the game theory. The proposed mission decision-making method of antagonized airfight is validated by some simulation examples of a swarm of unmanned combat aerial vehicles (UCAVs) that carry out the mission of the suppressing of enemy air defenses (SEAD).

1. Introduction

The team of multiple aircrafts has stronger capability than a single aircraft in detecting the targets, piercing through the defense systems, and carrying out the attack mission. Each member of the team can share the information acquired by any other one and carry out mission of cooperative attacking targets according to its position in air and the resources of fighting for a uniform airfight intention. The team of multiple aircrafts is able to form easily all kinds of vertiginous attack situation in airfight so that those opposed targets will be confronted with the defending difficulties. Thereby, the fashion that multiple aircrafts cooperatively attack targets will be the main pattern in future airfight.

In this paper, the phrase of attacking effect consists of validity, invalidity and uncertainty. The validity and invalidity of attacking effect are defined as the advantage acquired by our aircrafts (or foe's targets) and the cost paid for achieving intention by our aircrafts (or foe's targets) in antagonized airfight, respectively. Sensors aboard aircraft affect the attacking effect of aircraft due to the capability of sensors in detecting, tracking and identifying target, while weapons aboard aircraft

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affect the attacking effect due to the capability of weapons in hitting and destroying target. However, the above capabilities of sensors and weapons all rest with the distance, azimuth and pitching between one of our aircrafts and one of foe's targets. Accordingly, the fuzzy mapping function of the fighting effect of sensor and weapon is constructed by selecting the three position parameters of distance, azimuth and pitching as variables for establishing the correspondence between the position parameter and the ability of sensor and weapon. In this paper, the Dempster-Shafer (D-S) synthesize rules are used for formulating the situational assessment method.

When multiple aircrafts in our team are antagonizing some foe's targets simultaneously, one of our aircrafts is able to either detect and identify the foe's targets by sensors aboard the aircraft or receive the information of the foe's targets by wireless data link. Therefore, in this paper, we suppose that our team of multiple aircrafts has known the position and identity of all foe's targets and is able to acquire the important reasoning from the position and identity of foe's target to the capability of sensors' detecting and weapons' attack, the defending strategies and the advantage (showed by numerical value) acquired by selecting a certain defending strategy. If the above situation of antagonizing airfight is analyzed by quoting the game theory model, the situation means that our team has known the opponents and the opponents' strategies and cost function. Considering that our opponent is powerful, we think that our opponent also has known the equivalent information about our team of multiple aircrafts at least. We suppose that our team and our opponent simultaneously carry out action for equality because they all try to be the first actor. In this paper, the static non-cooperative and nonzero Nash games are used for formulating the mission decision-making method.

In recent years, a significant shift of focus has occurred in the field of autonomous unmanned combat aerial vehicles (UAVs) as researchers began to investigate problems involving multiple UAVs rather than single UAV. As a result of this focus on multiple UAVs, coordination of multiple UAVs has received significant attention.[1–3] Moreover, cooperative systems are required to operate in an adversary environment (such as suppressing of enemy air defenses (SEAD)).[4,5] Cooperative decision-making for multi-UAV or multi-Agent system is of great interest. A significant amount of current research activities focuses on a theoretic control framework for distributed cooperative decision-making for an ensemble of UAVs, and all the used research methods in this field are similar in Refs.[6–8] Additional autonomous decision-making focusing on mission planning, target assignment, or operation management of complex system can be found in Refs.[9–14] Solutions to general UAV cooperative decision-making problems in adversarial environments can be obtained by solving game problems introduced and implemented in Refs.[15–17] Related application information of game theory method appears in many sources.[18,19] A synthetic method for situation assessment based on fuzzy logic and D-S evidence theory is proposed in Refs.[20,21]

This paper develops a mission decision-making algorithm based on the game model, and then proposes a situational assessment algorithm based on the D-S evidence synthesize rules for a swarm of UCAVs in SEAD mission. In Section 2, a situational assessment algorithm of coordinated airfight is presented in detail and the D-S evidence theory is introduced simply for sustaining the mentioned situational assessment algorithm above. In Section 3, a mission decision-making algorithm is designed by formulating the strategies and cost function in the game model. Section 3 is based on Section 2. Section 4 shows an simulation example of a typical mission performed by a swarm of UCAVs. In Section 5, the simulating results in Section 4 are analyzed deeply. Section 6 summarizes the conclusions.

2. Formulating situational assessment based on evidence theory

2.1. Preliminaries

For sustaining the situational assessment algorithms mentioned in the previous section, the basic concepts of the D-S evidence theory are first introduced in the following part.

Let Θ be a set consisting of all the values that X might be and an element of set Θ is not consistent with the other elements, and then Θ is called as the discernment frame of X.

Definition 1. Let Θ be a frame of discernment, and if the function $m : 2^{\Theta} \rightarrow [0, 1]$ fulfills the following conditions:

(1) $m(\varnothing) = 0$
(2) $\sum_{A \subset \Theta} m(A) = 1$

then m is called as the basic probability assignment on the frame of discernment Θ and $m(A)$ is called as the basic probability number of A. $m(A)$ denotes the believed degree of A oneself.

Definition 2. Let Θ be a frame of discernment, and if the function $m : 2^{\Theta} \rightarrow [0, 1]$ is the basic probability assignment on Θ, then the function $\mathrm{Bel} : 2^{\Theta} \rightarrow [0, 1]$ is called as the belief function and is defined by

$$\mathrm{Bel}(A) = \sum_{B \subset A} m(B) (\forall A \subset \Theta)$$

where $\mathrm{Bel}(A)$ denotes the believed degree of A including all of its subsets.

D-S synthesize rules. Let $\mathrm{Bel}_1, \mathrm{Bel}_2, \cdots, \mathrm{Bel}_n$ be the belief functions on the same frame of discernment $\Theta, m_1, m_2, \ldots, m_n$ are the basic probability assignments correspondingly. If $\mathrm{Bel}_1 \oplus \mathrm{Bel}_2 \oplus \ldots \oplus \mathrm{Bel}_n$ is existent and has the basic probability assignment m, then

$$\begin{cases} \forall A \subset \Theta, A \neq \varnothing, A_1, A_2, \ldots, A_n \subset \Theta \\ m(A) = K \sum\limits_{\substack{A_1, A_2, \ldots, A_n \subset \Theta \\ A_1 \cap A_2 \cap \ldots \cap A_n = A}} m_1(A_1) m_2(A_2) \ldots m_n(A_n) \\ K = \left(1 - \sum\limits_{\substack{A_1, A_2, \ldots, A_n \subset \Theta \\ A_1 \cap A_2 \cap \ldots \cap A_n = \varnothing}} m_1(A_1) m_2(A_2) \ldots m_n(A_n) \right)^{-1} \end{cases}$$

where K is the middle parameter, and A_1, A_2, …, A_n are subsets of the discernment frame element A.

The D-S synthesize rules reflect the effect of combined operations made by many evidences.