Engineering Applications of Artificial Intelligence 39 (2015) 132–145

Contents lists available at ScienceDirect

Engineering Applications of Artificial Intelligence

journal homepage: www.elsevier.com/locate/engappai

Route evaluation for unmanned aerial vehicle based on type-2 fuzzy sets

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ARTICLE INFO

Article history:
Received 7 August 2013
Received in revised form
21 August 2014
Accepted 13 November 2014
Available online 25 December 2014

Keywords:
Route evaluation
Multi-criteria decision making (MCDM)
Aircraft survivability
Type-2 fuzzy sets (T2 FSs)
Computing with words (CWW)

ABSTRACT

Until now, routes evaluation for unmanned aerial vehicle still faces a variety of difficulties, which is due to the fact that during route evaluating, subjective judgments, quantitative data, and random information need to be considered simultaneously. In this paper, by formulating route evaluation as a multi-criteria decision making problem including uncertainties, an integrated route evaluation approach based on type-2 fuzzy sets is proposed. Firstly, a systemic evaluation framework that incorporates models for scoring evaluation criteria is proposed. Specifically, a survivability model incorporating dynamics and uncertainties in battlefield is developed, including some special features, such as calculating the probability of detecting, tracking, and destroying an unmanned aerial vehicle, and modeling the location of pop-up threats as a Markov chain. Then, type-2 fuzzy sets are introduced to represent linguistic values, managing linguistic uncertainty effectively and making the evaluation process realistic and reliable. Finally, the architecture of perceptual computer is extended, and the computing with words engine by means of linguistic weighted average method is adopted to obtain the overall score of each route, enabling both random and fuzzy uncertainties existing universally in the data to be effectively managed in a unified format. The proposed method has the advantages of diverse inputs such as numbers, probability distributions and words. All these can be aggregated to a final decision. Furthermore, it provides a useful tool to handle route evaluation problem in a highly reliable and intelligent manner, and it can be applied to solve multi-criteria decision making problems in many disciplines. Experimental results demonstrate the feasibility and effectiveness of our method.

1. Introduction

Unmanned aerial vehicles (UAVs) are aircrafts without onboard pilots that can be remotely controlled or fly autonomously based on pre-planned flight routes, increasingly being used in real-world applications (Peschel and Murphy, 2013). UAV flight route is vital for mission effectiveness, UAV's survivability, ground operating, and support costs. Such a route is usually automatically provided by a route planner based on a cost function (Zheng et al., 2005). However, in some cases, the predetermined cost function cannot account for all potential external conditions or relevant variables. Therefore, the optimal or near-optimal route provided by the route planner may not represent a desirable solution for many mission scenarios and could result in erroneous or misleading decision support (Cummings et al., 2012). An effective way to handle these issues is multi-route planning, where several candidate routes are planned. And in real applications, a suitable flight route is chosen from these alternative routes according to mission characteristics. Therefore, decision making among alternative routes for UAVs is required in real applications (Liu et al., 2011; Ruz et al., 2007).

Performance of a UAV flight route is evaluated against the mission effectiveness of the UAV when flying along given route, taking into consideration battlefield environments and mission characteristics. Until now, series of mission effectiveness assessment approaches have been proposed in some mission planning systems, and the majority of them fall into the following categories: (1) analytic methods (Jun et al., 2008), which apply functional representations describing the relations between effectiveness variable factors and given combat situations to approximate mission effectiveness; (2) operational simulation methods (Ender et al., 2010), where effectiveness values can be calculated by computer based simulations directly or through statistical processing; (3) expert evaluation methods (Kangaspunta et al., 2012), where criterions reflecting mission effectiveness are chosen firstly, and then military experts make judgments on the scores and weights of the criterions. Finally, mission effectiveness values are acquired by dealing with the experts' judgments on the scores and weights of the criterions (Lin and Hung, 2011; Wang and Chang, 2007). There are

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http://dx.doi.org/10.1016/j.engappai.2014.11.008

also researches using combination methods or multiple data source approaches to improve the reliability and robustness of the evaluation results (Lee et al., 2010). With respect to the UAV route evaluation problem, each method has its own merits and deficiencies owing to the specific characteristics:

(1) Various factors contribute to the performance of a given flight route, e.g., mission, threats, terrain, and dynamic battlefield environment.
(2) There are multi-hierarchy and multi-level route characteristics, such as length, smoothness, risk, and mission performance. These route characteristics are often in conflict and non-commensurable.
(3) Different types of information need to be considered and accurately represented, such as quantitative data, qualitative judgments of experts, and probability distributions.
(4) Different kinds of uncertainties, such as fuzziness, randomness and so on, may exist in the decision environment. It is necessary to deal with these uncertainties within the same evaluation framework.

Until now, comprehensive or well documented route evaluation criterions and methods are lacking. Therefore, a systematic and transparent evaluation framework is needed to guide the assessment process, which should contain features describing the multiple conflicting route characteristics as well as representing dynamics and uncertainties in the decision environment.

Aircraft survivability is a key feature that contributes to overall route performance. Conventional approaches of survivability modeling usually focused only on selected factors and were under some assumptions, which were reductionist to some extent in nature. For example, in most studies, route risks were calculated by approximating to the exact solutions (Duan et al., 2010; Berger et al., 2012), but the survivability was not accurately accounted. Therefore, an integrated survivability model is required to evaluate the route scientifically and realistically.

As stated previously, to evaluate a route, one has to make trade-offs among various route characteristics. Trade-offs are characterized by the weight parameters usually assigned according to trail-and-error experience of experts (Berger et al., 2012; Fu et al., 2013; Goerzen et al., 2010; Roberge et al., 2013; Zheng et al., 2005). Actually, experts' judgments and preferences are linguistic and fuzzy in nature. One way to represent linguistic variables is to use the fuzzy logic approach to associate each linguistic term with a possibility distribution (Zadeh, 1971). Aspects related to the representation of linguistic values are typically ignored in most of the studies concerning UAV flight route evaluation. Several research studies tried to account for the linguistic uncertainty and ambiguity elements in the route evaluation decisions based on type-1 fuzzy sets (T1 FSs) (Garcia et al., 2009; Kala et al., 2010). However, words mean different things to different people, and there are at least two types of uncertainties associated with a linguistic term (Wallsten and Budescu, 1995): intrapersonal uncertainty and interpersonal uncertainty. T1 FSs have limited capabilities to directly capture interpersonal uncertainty. Therefore, a theoretical method is required in the route evaluate model to manage high levels of uncertainty in the subjective knowledge of experts.

The concept of type-2 fuzzy sets (T2 FSs) introduced by Zadeh is an extension and generalization of T1 FSs (Zadeh, 1975; John and Coupland, 2007). Based on Zadeh's concept of a T2 FS, Karnik et al. developed operations on T2 FSs and introduced the concept of type-reduction for T2 FSs (Karnik and Mendel, 2001). Since late 1990s, T2 FS theory has been well-developed in the literature, and type-2 fuzzy logic systems (T2 FLSs) have become an active research topic. Mendel et al. provided the wavy slice representation for T2 FSs, and studied how T2 FLSs can be analyzed based on wavy slice representation (Mendel and John, 2002; Mendel et al., 2006). Liu (2008) and Wagner and Hagras (2010) developed the α-plane representation and zSlice representation for T2 FSs. Based these representations, multiple studies analyzed and explored functions, uncertainty measures and type-reduction methods for T2 FSs (Wu and Mendel, 2009; Wu et al., 2012). Wu et al. introduced how T2 FSs and related computations could be exploited in making subjective judgments by computing with words (CWW) (Wu and Mendel, 2010). In recent years, T2 FSs have been successfully applied in a variety of areas (Dereli et al., 2011), such as: traffic management (Balaji and Srinivasan, 2011), industrial control (Kumbasar et al., 2011), and electric load forecasting (Lou and Dong, 2012).

In this paper, we model UAV route evaluation as a multi-criteria decision making problem with uncertainties and propose a comprehensive route evaluation approach based on T2 FSs. Firstly, we identify the factors that have significant effects on route evaluation process and build a generic hierarchical criteria framework. With the consideration of random uncertainty in the battlefield environment, we develop a survivability model. Then, we introduce T2 FSs to model subjective judgments, effectively addressing linguistic uncertainty associated with words used by experts. Finally, we apply probability–possibility transformation to map survivability probability distributions into fuzzy sets, use CWW engine (Wu and Mendel, 2010) to aggregate a wide range of data, as a result, this new method can enable both random and fuzzy uncertainties to be aggregated and reflected.

The rest of this paper is organized as follows. Section 2 provides brief descriptions of the proposed route evaluation method. Details of the mathematical models of each criterion and sub-criterion are then presented in Section 3. The proposed route evaluation method by using T2 FSs is described in Section 4. The experimental results are given in Section 5. Finally, the paper is concluded in Section 6.

2. Route evaluation modeling

2.1. Proposed method

Typically, a UAV flight route is characterized by a variety of features or characteristics. Evaluation must not just focus on UAV's mission performance, but also on its ability to survive a wide variety of threats and situations, at an affordable fuel cost and safety level. Therefore, route evaluation can be considered as a multi-criteria decision making problem, where several evaluation criteria like length, mission performance, and risk need to be weighed against each other. Scores of criteria are computed based on their calculation models, and trade-offs among various criteria are determined by weight factors specified by military experts.

As mentioned previously, various kinds and sources of uncertainties exist in the decision environment, which can be classified as aleatoric uncertainties or epistemic uncertainties (Ross et al., 2013). Due to aleatoric (stochastic) uncertainties such as the appearance of pop-up threats, survivability of a route is also uncertain. To deal with these random factors and embed them into the final decision, the survivability of a route is represented by its probability density function (histogram). Epistemic uncertainties arising from fuzziness are also known as subjective uncertainties. Experts' uncertainty about the weights of criteria is a representative kind of epistemic uncertainty, which is handled by T2 FSs (possibility distributions) in this study. To integrate these different kinds of uncertainties within the same evaluation framework, each survivability probability distribution is transformed into a fuzzy set based on probability–possibility transformation theory (Dhar, 2013; Dubois and Prade, 1983; Dubois et al., 2008; Sakallı and Baykoç, 2011). Probability-possibility transformation has been studied by many researchers,