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Article

A fuzzy path selection strategy for aircraft landing on the carrier

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Abstract: Landing is one of the most dangerous tasks in all the operations on the aircraft carrier, and the landing safety is very important to the pilot and the flight deck operation. The problem of landing path selection is studied in this paper as there several candidates corresponding to different situations. A fuzzy path selection strategy is proposed to solve the problem considering the fuzziness of environmental information and human judgment, and the goal is to provide the pilot with more reasonable decision. The strategy is based on Fuzzy Multi-attribute Group Decision Making (FMAGDM), which has been widely used in industry. Firstly, the background of the path selection problem is given. Then the essential elements of the problem are abstracted to build the conceptual model. A group decision-making method is applied to denote the preference of each decision maker for each alternative route, and the optimal landing path under the current environment is determined taking into account the knowledge and the weight of both decision makers. Experimental studies under different setups, i.e., different environments, are carried out. The results demonstrate that the proposed path selection strategy is validated in different environments, and the optimal landing paths corresponding to different environments can be determined.

Keywords: landing, aircraft carrier, landing path, fuzziness, fuzzy multi-attribute group decision making

1. Introduction

Aircraft landing on the carrier is a task with high risk [1]. An aircraft can land on the carrier successfully with the probability of 70%, and the rate is lower at night. In comparison with land-based aircraft, landing on an aircraft carrier is more dangerous and complicated since a series of particular conditions needs to be taken into account. Besides, the flight condition and the maritime environment are changing all the time, and these uncertainties make the landing task difficult [2-3]. In order to guide the aircraft landing safely, an aircraft carrier must be equipped with certain special guidance devices such as the Fresnel lens optical landing system [4], the all-weather radar landing system [5] and so on. Besides, a variety of commanders and staffs are needed to guarantee the landing safety of aircraft and cope with all emergencies [6]. Among them, the landing console operator (LCO) onboard is responsible for supervising the aircraft which are about 20 nautical miles away from the aircraft carrier. The landing signal officer (LSO) concentrates on the last step of landing, and he assists the pilot to land safely using the body language or by talking to the pilot directly [7]. The air officer in the control tower does the work related to the flight deck, e.g., preparing flight deck for launching, managing the carrier aircraft on the flight deck and emptying the deck for landing. Each staff mentioned above takes their own duty at different stages of landing, and the landing safety of aircraft is accomplished by their team work.

In each landing stage, the above commanders and staffs make a decision to guide the aircraft in a very short time based on their knowledge and the information shown on various instruments, which makes high-level demands on the judgment and reaction of them [8]. However, there is fuzziness in the environment and flight information, and accurate judgment cannot always be reached quickly, which attributes to the complicacy and variability of weather at sea, the lack of comprehensive information and other subjective factors affected. In recent years, artificial intelligence (AI) is widely applied to various fields and many great achievements have been made in this field. For instance, the complex changes and uncertainties in manufacturing can be managed by AI and machine learning techniques [9]. Another case in point is the routing problems for ground vehicles, and minimal total cost can be achieved using AI without violating the capacity and time window constraints [10]. Correspondingly, there exists a high possibility that the idea of AI can be introduce to the landing path selection system of aircraft in order to solve the fuzziness and reduce the workload of the staffs onboard. Furthermore, a new AI-based path selection strategy is expected to response quickly with more accurate judgment and improve the safety level of the landing.

Currently, a large amount of researchers concentrate primarily on the analysis of landing safety, the modeling of LSO's action and the establishment of variable strategy pilot model. For example, the landing safety is analyzed based on the rough set theory, and the values of kinematical parameters and their combinations are determined to define the boundary conditions for safe landing [11]. The action of LSO is described by a fuzzy language, and multiple AI techniques are applied to the landing decision-support tool. The obtained landing decision-support tool allows the LSO to make better time-critical decisions in a dangerous environment [12]. The gesture of the LSO is also studied extensively, and a multi-signal gesture database, which requires both body knowledge and hand knowledge of the LSO to distinguish gestures, was introduced. Subsequently, the true meaning of gestures obtained based on the gesture database is communicated to the pilot to enable a better understanding and assist landing [13]. Our team also conducted research intensively on the automatic landing guidance technology. A model of LSO was found for the digital simulation of a pilot-carrier system on the basis of analyzing the behaviors of LSO in the final stage of landing. Fuzzy logic laws were used to model three kinds of behaviors of the LSO. Afterwards, the carrier motion prediction of the LSO is described by a neural network model, and the model was verified by simulating landing under several kinds of conditions [14]. In the aspect of studying the pilot behaviors, a variable-strategy pilot model is established for landing. This model is comprised of two switchable components: a discrete component of the acquisition strategy for a large deviation of the glide path and a continuous component of the pursuit tracking strategy for a small deviation [15]. The cited literature can explain the work of LSO, and mathematical models are established to describe the LSO's action. They presented solid research work on the automatic landing guidance technology and have potential significance in the landing safety of aircraft. The issue of landing path for aircraft carrier is also an important part of the automatic landing guidance technology. Unlike the unmanned aerial vehicles (UAV) path planning problem [16], the landing path of manned aircraft is fixed and only can be selected from several candidate modes. Therefore, instead of planning the landing path, it is determined before the aircraft is ready to reach the carrier, and determine the landing path is also a part of the LCO's work. However, no relevant literature has been reported on this issue so far. As the landing path selection is the first step to guide the aircraft landing, it is important to the automatic landing system and thus worthwhile to be studied intensively.

Similar to land-based aircraft, aircraft on the carrier receive the position information from the onboard equipment and use this information to confirm its location before approaching the carrier. As the carrier is moving all the time, the pilot has to keep in touch with the flight control center and correct the path constantly according to the feedbacks from the flight control center. According to the performance, the traffic conditions, a variety of weather conditions and visibility, the pilot selects one of the candidate paths. However, if the pilot senses the shortage of aircraft fuel or a mechanical failure occurred to the aircraft, he has to communicate with the LCO directly to carry on air refueling or an emergency landing on the ground in land bases. In view of the fact that fuzziness of various factors and information are involved in the landing path selection problem [17], some unreasonable decisions may be made if the knowledge and experience of human are only depended on. Therefore, a landing path selection strategy is imperative to deal with the above defects, thus reducing the workload of staffs and improving the safety level of landing.

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The main contribution of this paper is to establish a mathematical model and provide a method to solve the landing path selection problem. This problem is a sort of decision-making problem which belongs to the air traffic management of carrier. To make a subjective judgment optimal and practical, a decision needs to be made based on reliable information and considering all constraints. Obtaining the environmental information quickly is essential to the decision-making in this problem. Moreover, how to process information according to the knowledge and experience is the key. The problem involves various elements and fuzzy information. Therefore, it is an unstructured decision-making problem. This kind of problem can only be solved based on the experience and flexibility of a decision maker or using an AI method. It is also worth noting that different decision makers may result in different judgments due to many reasons. For example, they obtain different information, they are assigned different flight tasks and objectives, or they have different understanding of performance criteria. Considering all the above-mentioned factors, this paper introduces a group decision-making scheme, which is an effective method to coordinate the above differences and result in a reasonable decision.

2. Problem statement and conceptual model establishment

In this section, the landing path selection problem will be described firstly, and then the essential elements involved in the problem are discussed. A brief conceptual model is given at the end of this section to give an overview for solving this problem.

2.1 Problem statement

According to the tactical imperatives, aircraft receives the returning information from the air control system on the carrier. To ensure the safety of returning flight, the real-time position information is provided by the Tactical Air Navigation (TACAN), which contains the relative position to the carrier. Besides, the returning aircraft is also instructed by an airborne early warning (AEW), which provides the returning aircraft with the overall air traffic situation. The information from an AEW is essential when managing the landing paths for a large amount of airplanes in order to guarantee a safe and orderly landing. The sea weather is obtained through the observatory on the carrier and is transmitted to a pilot. To sum up, the landing path selection problem is a process that the pilot and LCO combine/analyze various information and make quick decision accordingly. The details of the problem can be further shown in Figure 1.

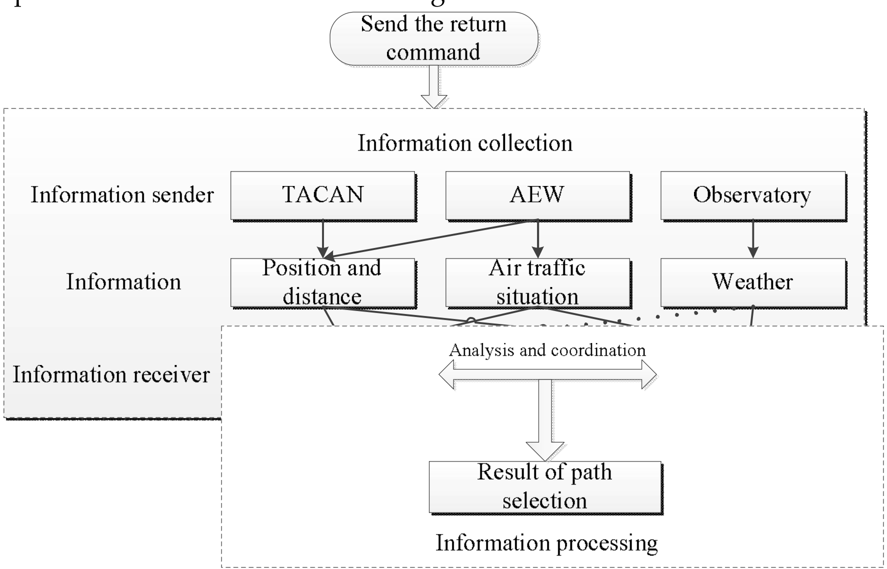

Figure 1. Description of the landing path selection problem.

The dotted line in Figure 1 denotes that when the pilot selects the optimal landing path, he/she just treat the weather information as a reference instead of relying on it to make a judgment. This is because the weather information is relative to the carrier, and there may be differences between the

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places around the aircraft and around the carrier. This explains why the pilot just regards the weather information from an observatory as a reference.

In Figure 1, the pilot and the LCO are the decision makers when determining the optimal landing path. Besides, the LCO is the major decision maker because he/she masters the air traffic situation better thus enhancing the safety level of landing. What's more, the feeling of a pilot is considered limitedly although he/she has a comprehensive understanding of the weather information and the performance of the aircraft. The reason is as follows. In actual work, the pilot usually has a heavy workload, e.g., executing a flight mission and analyzing various information simultaneously, therefore, he/she will be distracted from other work and his/her judgment will be affected accordingly.

2.2 Essential elements

According to the problem description, there are several essential elements in the path section problem: the decision makers, the alternative landing paths and the contributing factors. The decision makers have been analyzed above, the rest two will be discussed in this section.

1. The alternative landing paths:

There are four modes of landing path according to the differences in atmospheric environment, performance of an aircraft and the air traffic situation, as listed below.

① l_1: The weather, visibility, performance of an aircraft and air traffic situation are all in good conditions.

The pilot lands the aircraft by vision under such conditions. The aircraft flies counterclockwise following the rectangular route above the carrier, as shown in Figure 2.

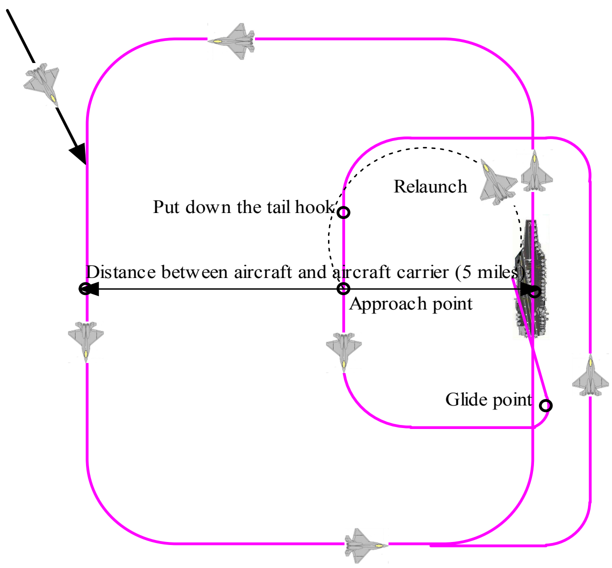

Figure 2. General view of alternative landing path l_1

The carrier is located in the center of the right edge of the rectangle at this moment. If the aircraft keeps waiting for the landing command, it will fly counterclockwise following the rectangular path and get in touch with the approaching operation person every time it passes the carrier to confirm the landing permission.

② l_2: The weather and visibility are at a medium level and the performance of the aircraft and air traffic are in good conditions.

A landing mode with higher safety standard will be adopted when the clouds appear between the height of 1000 and 3000 feet and cover more than 5/8 of the sky. It becomes dangerous to land the

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aircraft by vision due to the heaviness of clouds. Therefore, a landing path called "Martial Pattern" is set 15 miles away from the carrier to guarantee the landing safety, as shown in Figure 3. The aircraft will repeat the "Martial Pattern" until it is permitted to land.

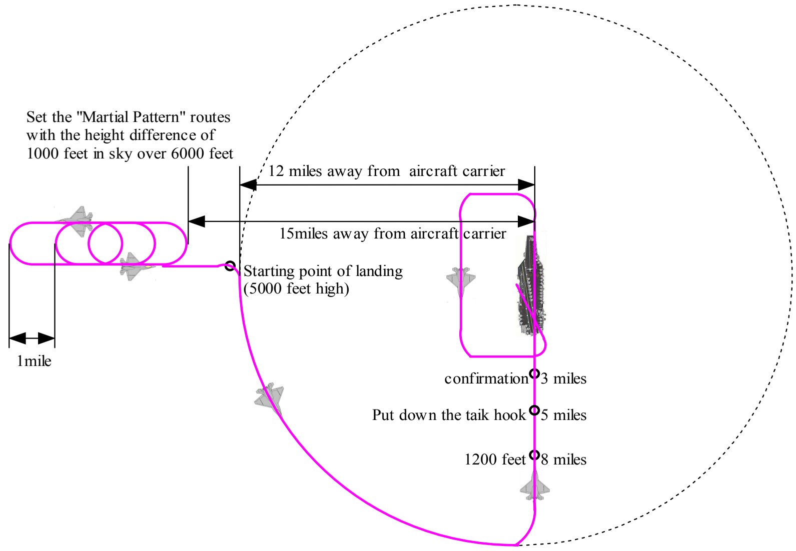

Figure 3. General view of alternative landing path l_2

③ l_3: The weather and visibility are bad, but the performance of the aircraft and the air traffic are in good conditions.

It is also unsafe to for the pilot to land the aircraft by vision in such conditions. Similarly, "Martial Pattern" is set 15 miles away from the carrier and the aircraft repeats the "Martial Pattern" before being permitted to land, as shown in Figure 4. Unlike in the case of l_2, the aircraft does not have to fly a rectangle route around the carrier after receiving the landing permission. Instead, it approaches the carrier directly with gliding.

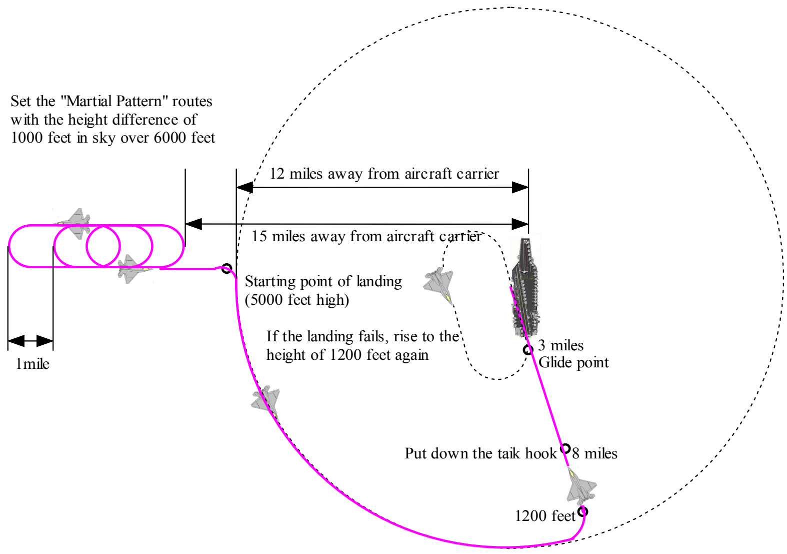

Figure 4. General view of alternative landing path l_3

④ l_4: The performance of aircraft is poor or the air traffic is in a bad condition.

There are no proper conditions for aircraft landing on the carrier. In this case, the pilot has to get in touch with the land base for emergency landing.

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2. The contributing factors:

According to the analysis on the alternative landing paths, the contributing factors for the landing paths selection problem can be concluded as follows:

①Weather

It is usually difficult to predict the weather around a large area accurately because no obstacles exist above the sea and the air flow above the sea is active. Therefore, the weather information is obtained by mastering the nearby weather condition continuously. Usually, l_1 l_2 and l_3 are chosen for good, medium and bad weather respectively.

②The height of clouds

The vision of a pilot will be impaired when the clouds are low or cover a wide range of the sky. The heavy cloud may even lead to a bump of an aircraft during the fight. Therefore l_1 is preferred when there are few or no clouds. Otherwise l_2 or l_3 which enjoy higher safety standard will be preferred.

③Visibility

The level of visibility plays an important role in affecting the visual observation and the judgment of a pilot. Good visibility often leads to choose l_1 or l_2. On the contrary, l_3 or even l_4 will usually be chosen for poor visibility.

④Performance of aircraft

The aircraft is usually in good performance during the flight and will land on the carrier according to the command received. However, the aircraft may get damaged when accidents occur, l_4 will be the best choice in this case to guarantee the landing safety.

⑤Air traffic situation

It refers to the status of other aircraft near the landing aircraft. If the air traffic is crowded or the returning schedule fails, l_4 provides a safe landing solution.

2.3 The conceptual model

Based on the description of the landing path selection problem and the analysis of its essential elements, the key components involved in the problem are abstracted, and a conceptual model is established, see Figure 5, to provide the reader a general idea of decision-making when solving this problem.

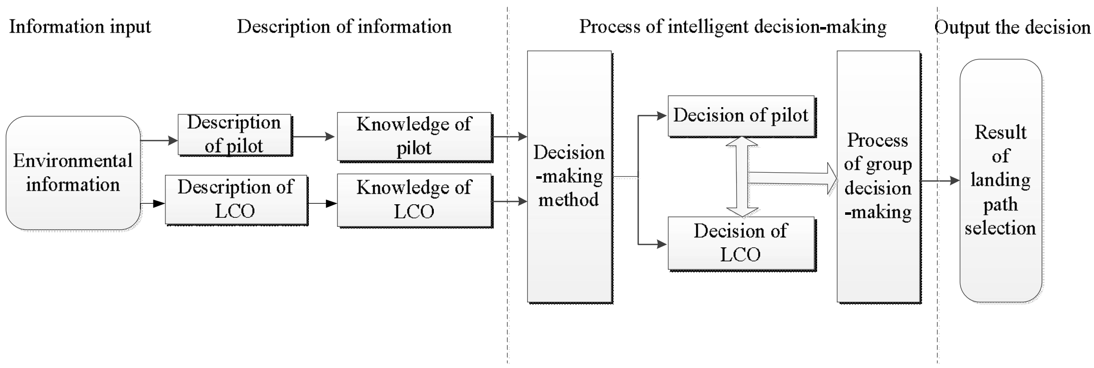

Figure 5. Conceptual model of the landing path selection problem

3. FMAGDM (Fuzzy Multi-attribute Group Decision Making)-based path selection method

The conceptual model provides a general idea of decision-making. Mathematical descriptions of the essential elements are needed to establish the model. Since it is difficult to describe the real-time environmental information quantitatively, the judgment of a single pilot or a single LCO is often inaccurate. Therefore, it is necessary to develop a comprehensive decision-making method which integrates the judgments of both the pilot and the LCO to make the final decision more scientific and

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reasonable. In view of the abovementioned characteristic, the FMAGDM method can describe the environmental information and the weights of decision-makers [18-20] and is suitable for solving the path selection problem. To be specific, the fuzzy TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) approach [21, 22] is developed, and the triangular membership function is used to describe the performance ratings of contributing factors (short for PRCF for convenience in the rest of this paper) and the current environmental vector. Then a mathematical model is established to evaluate each alternative landing path. To coordinate the decisions of the pilot and the LCO, the group decision-making method based on fuzzy judgment is introduced to rank the alternative landing paths. Finally, the optimal landing path under the current environment is obtained.

3.1 The PRCF and the current environmental vector

In the process of building a decision-making model, the PRCF or the current environmental vector need to be described using fuzzy linguistic variables. The triangular membership function is then introduced to define the value of each fuzzy linguistic variable. For example, "low", "medium" or "high" is used to express the performance rating of l_1 with respect to the weather, and the triangular membership function is used to define "low", "medium" or "high". Therefore, the triangular membership function is the foundation of establishing the decision-making model. The concept and properties of the triangular membership function are presented below to ensure a better understanding of its application in the path selection problem [23].

Definition 1: Let $a=[a^L,a^M,a^U]$ be a triangular membership function with $0<a^L\le a^M\le a^U$, as shown in Figure 6.

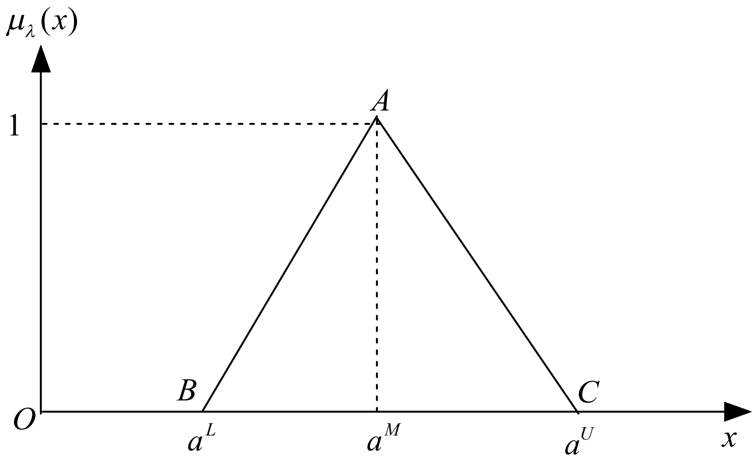

Figure 6. The triangular membership function

An example is presented to make a clear understanding of its function in describing the current environmental vector. Triangular membership function a is used to describe good visibility. The plots indicate that the possibility for this case, i.e., the current visibility belongs to the "good visibility", increases from point B to point A and reaches the maximum in point A. On the contrary, the possibility decreases from point A to point C and reaches the minimum in point C.

Definition 2: The mean value of a triangular membership function a is defined as

$$s(a)=(a^L+2a^M+a^U)/4 \tag{1}$$

The mean value property is used to sort the triangular membership functions. In view of the triangular membership functions a and b, there is a definition as follows: $a\ge b$ if $s(a)\ge s(b)$

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and $a < b$ if $s(a) < s(b)$. For example, if a and b describe different performances of an aircraft, $a \geq b$ denotes the performance described by a is better than that described by b in general.

Definition 3: Assume U is a universe of discourse and the α-cut set a_α is defined as

$$a_\alpha = \{x \in U \mid \mu_\lambda(x) \geq \alpha\}, \alpha \in [0,1] \tag{2}$$

where a_α can be denoted as $a_\alpha = [a^L(\alpha), a^R(\alpha)]$, as shown in Figure 7. If a presents the medium weather, a_α denotes that the degree of that is more than α.

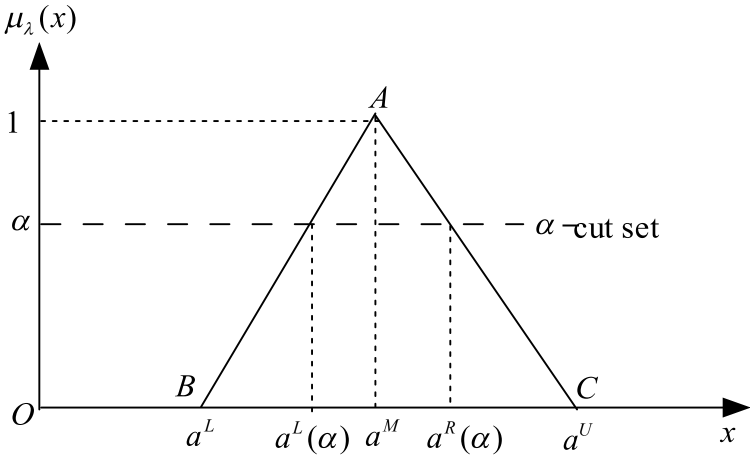

Figure 7. Definition of α-cut set in triangular membership function

Definition 4: Given triangular membership functions $a = [a^L, a^M, a^U]$ and $b = [b^L, b^M, b^U]$ with $a \geq b$, the fuzzy distance between a and b is defined as follows.

$$d(a,b) = [\max\{\int_0^1 d^L(\alpha)d\alpha, 0\}, d^L(1), \int_0^1 d^R(\alpha)d\alpha] \tag{3}$$

where $d^L(\alpha)$ and $d^R(\alpha)$ are defined as below:

$$\begin{cases} d^L(\alpha) = a^L(\alpha) - b^R(\alpha) \\ d^R(\alpha) = a^R(\alpha) - b^L(\alpha) \end{cases} \tag{4}$$

Similar to the definition of a distance in a geometric space, the fuzzy distance also represents the degree of approximation between these two triangular membership functions. For example, suppose that a and b describe good and bad air traffic situation respectively, then $d(a,b)$ represents how large the difference is between these two air traffic conditions. It should be noted that $d(a,b)$ is also a triangular membership function.

Up to now, the knowledge of triangular membership function, which is used to describe the fuzzy linguistic variables when establishing a decision-making model, has been given. Besides, some main operations associated with triangular membership functions are listed below (a and b are two random triangular membership functions, k is a random real number):

$$① a + b = [a^L, a^M, a^U] + [b^L, b^M, b^U] = [a^L + b^L, a^M + b^M, a^U + b^U]; \tag{5}$$

$$② a \times b = [a^L, a^M, a^U] \times [b^L, b^M, b^U] = [a^L \times b^L, a^M \times b^M, a^U \times b^U]; \tag{6}$$

$$③ k \times a = [k \times a^L, k \times a^M, k \times a^U]; \tag{7}$$

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④ $a^{-1} = [1/a^U, 1/a^M, 1/a^L].$ (8)

3.2 Decision-making process with the developed fuzzy TOPSIS approach

The weather condition, cloud height, visibility, performance of aircraft and air traffic situation are the five key contributing factors determining the result of landing path selection which can be written as f_1, f_2, f_3, f_4 and f_5 respectively. The PRCF are described by triangular membership functions. Among the five contributing factors, only the performance ratings of clouds height and visibility can be described quantitatively, as shown in Table 1.

Table 1. Description of performance ratings for five contributing factors

	f_1	f_2	f_3	f_4	f_5
	Good	>3000 feet	>5 km	Medium	Good
	Bad	1000-3000 feet	>5 km	Good	Good
	Terrible	< 1000 feet	< 5km	Good	Good
	Indifferent	Indifferent	Indifferent	Bad	Bad

The above descriptions need to be unified with the same linguistic variables, as shown in Table 2.

Table 2. Unified linguistic variables of performance ratings

Linguistic variable	No	Low	Medium	High	Very high
Expression	NO	LO	ME	HI	VH

It should be mentioned that all the linguistic variables in Table 2 will be described by triangular membership functions later. Suppose that the performance rating of l_j $(j = 1,2,3,4)$ with respect to f_i $(i = 1,2,3,4,5)$ is denoted as $e_{ij} = [e_{ij}^L, e_{ij}^M, e_{ij}^U]$ (the value of e_{ij} can be chosen from Table 2, then the fuzzy decision matrix for the path selection problem can be established as follows:

$$D = \begin{bmatrix} e_{11} & e_{12} & e_{13} & e_{14} \\ e_{21} & e_{22} & e_{23} & e_{24} \\ \vdots & \vdots & \vdots & \vdots \\ e_{51} & e_{52} & \cdots & e_{54} \end{bmatrix} \quad (9)$$

where matrix D is the knowledge base which has been mastered by the decision makers in advance.

Having introduced the basics of the developed fuzzy TOPSIS approach for solving the path selection related decision making problem, the detailed procedure will be described below.

Step 1: Normalize of the fuzzy decision matrix

Different contributing factors, e.g., the descriptions of f_2 and f_3, use different measurement units when collecting raw data. Therefore, normalization is needed to transform e_{ij} into the interval of [0,1] in order to eliminate anomalies. In this paper, a linear transformation is adopted to get the normalized fuzzy decision matrix X:

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} \\ x_{21} & x_{22} & x_{23} & x_{24} \\ \vdots & \vdots & \vdots & \vdots \\ x_{51} & x_{52} & \cdots & x_{54} \end{bmatrix} \quad (10)$$

Since the PRCF denote the efficiency in the path selection problem, x_{ij} can be normalized using the largest value, i.e., efficiency, of this contributing factor:

$$x_{ij} = [e_{ij}^{L} / e_{i}^{U\max}, e_{ij}^{M} / e_{i}^{U\max}, e_{ij}^{U} / e_{i}^{U\max}] \quad (11)$$

where $e_{i}^{U\max} = \max_{1 \le j \le 4} \{e_{ij}^{U}\} (i = 1, 2, ..., 5, j = 1, 2, 3, 4)$. Using Eq. (11), all linguistic variables can be transformed into the interval of [0,1].

The pilot and the LCO are regarded as the decision maker 1 and 2 respectively, and the normalized fuzzy decision matrix X_1 and X_2 can be established according to the knowledge and experience of decision makers.

$$X_1 = \begin{bmatrix} HI & ME & LO & NO \\ VH & HI & LO & NO \\ VH & VH & LO & LO \\ ME & HI & HI & LO \\ ME & HI & HI & LO \end{bmatrix}, X_2 = \begin{bmatrix} HI & ME & NO & NO \\ HI & ME & LO & NO \\ HI & HI & LO & NO \\ ME & HI & HI & ME \\ HI & VH & VH & LO \end{bmatrix}$$

Comparing X_1 with X_2, it can be found that the performance ratings of a pilot is higher than that of the LCO with respect to the atmospheric environment in general. This is because the pilot has true feelings of the atmospheric environment, and he/she is usually conservative for safety reason when determining the landing path. Besides, performance ratings with respect to the air traffic situation are set higher by the LCO compared to the pilot. This is because the LCO grasps comprehensive traffic information, and he/she puts higher priority on safety operation around the carrier.

Step 2: Integrate the current environment vector into the normalized fuzzy decision matrix

The environmental vector for the case under consideration can also be described using linguistic variable, as shown in Table 3.

Table 3. Linguistic variable of environmental vector (for a case under consideration)

Linguistic variable	Too poor	A little poor	Normal	Good	Very good
Expression	TP	LP	NO	GO	VG

The environmental evaluation of each contributing factor is denoted as $\omega_i = [\omega^L, \omega^M, \omega^U]$, which compose the environmental vector ($i = 1, 2, ..., 5$, the value of ω_i can be chosen from Table 3.

Then the normalized fuzzy decision matrix integrating the environmental vector can be calculated as follows:

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$$Z=(z_{ij})_{5\times 4}=(\omega_i x_{ij})_{5\times 4}=\begin{bmatrix} z_{11} & z_{12} & z_{13} & z_{14} \\ z_{21} & z_{22} & z_{23} & z_{24} \\ \vdots & \vdots & \vdots & \vdots \\ z_{51} & z_{52} & \cdots & z_{54} \end{bmatrix} \tag{12}$$

Step 3: Determine the positive and negative ideal solutions

The positive ideal solution is obtained when each PRCF chooses its highest value from the fuzzy decision matrix D, and the negative solution is obtained by choosing the lowest value for each performance rating. These solutions are called the ideal solutions because the corresponding cases are almost impossible to happen in reality.

The fuzzy positive ideal reference point (FPIRP) and negative point (FNIRP) are written as P and N for convenience. Besides, the FPIRP and FNIRP are defined as $P=(p_1,p_2,\ldots,p_5)$ and $N=(n_1,n_2,\ldots,n_5)$ with $p_i=\max_{1\le j\le 4}\{z_{ij}\}$ and $n_i=\min_{1\le j\le 4}\{z_{ij}\}$.

Step 4: Calculate the fuzzy distance between $l_j\,(j=1,2,\ldots,4)$ and P (or N)

According to Eq. (3), the fuzzy distance between $l_j\,(j=1,2,\ldots,4)$ and P (or N) are defined as follows:

$$d(l_j,P)=\sum_{i=1}^{5} d(z_{ij},p_i) \tag{13}$$

$$d(l_j,N)=\sum_{i=1}^{5} d(z_{ij},n_i) \tag{14}$$

The optimal landing path is the one which is close to the FPIRP and far away from the FNIRP. According to different distances from the FPIRP, a ranking list of all the alternative landing paths can be determined.

Step 5: Obtain the closeness coefficient

The larger the closeness coefficient is, the closer the alternative landing path is to the fuzzy ideal solution. The following formula is adopted to calculate the closeness coefficient and distinguish the importance between FPIRP and FNIRP.

$$C(l_j)=\mu\frac{d(l_j,P)}{d(l_j,P)+d(l_j,N)}+(1-\mu)\frac{d(l_j,N)}{d(l_j,P)+d(l_j,N)} \tag{15}$$

where $\mu(0<\mu<1)$ is a weight for different distances from FPIRP and FNIRP, and it is determined by the subjective attitude of a decision maker. If the atmospheric environment is good in general, the decision maker usually puts more attention on FPIRP and set μ as a smaller value. A larger value will be set for μ to put more attention on FNIRP if the air traffic situation is bad.

3.3 Process of the group decision-making

The decision of a pilot or a LCO can be calculated separately according to the above mentioned procedure. In reality, decision made by one of them may not be the optimal solution because

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different decision makers obtain different information and have difference in knowledge and preference. Therefore, to deal with the divergence and make an optimal decision, the decision of both the pilot and the LCO should be integrated. The group decision-making problem will be discussed and addressed in this section.

The main idea of solving the group decision-making problem is to regard the pilot and the LCO as two contributing factors. Then the group decision-making problem can be translated into a single person decision-making problem [24]. The group fuzzy decision matrix is constructed as follows:

$$O=\begin{bmatrix} o_{11} & o_{12} & \cdots & o_{14} \\ o_{21} & o_{22} & \cdots & o_{24} \end{bmatrix} \quad (16)$$

where $o_{st}(s=1,2;t=1,2,3,4)$ is the closeness coefficient $C(l_j)$, which is calculated for each decision maker using Eq. (15). The group decision-making solution is depicted in detail by the following steps:

Step 1: The matrix O is a normalized fuzzy decision matrix by itself so the step of normalization can be skipped. We assume the weights of pilot and LCO as $\lambda_1=[\lambda_1^L,\lambda_1^M,\lambda_1^U]$ and $\lambda_2=[\lambda_2^L,\lambda_2^M,\lambda_2^U]$ respectively. The weighted normalized group fuzzy decision matrix can be calculated in the same way as in section 3.2 and is written as $V=(v_{kj})_{2\times 4}(k=1,2;j=1,2,3,4)$. Note that the opinion of the LCO should be granted greater weight due to the fact that the LCO is less subject to many kind of distraction compared to a pilot. On the other hand, the opinion of the pilot should be also taken into account since he/she has a better feeling in weather and knows better the current aircraft performance.

Step 2: Write the fuzzy positive group ideal reference point (FPGIRP) and negative point (FNGIRP) as GP and GN respectively. The FPGIRP and FNGIRP can be formulated as $GP=(gp_1,gp_2)$ and $GN=(gn_1,gn_2)$ where $gp_k=\max_{1\le j\le 4}\{v_{kj}\}$ and $gn_k=\min_{1\le j\le 4}\{v_{kj}\}$.

Step 3: Calculate the fuzzy distance and the closeness coefficient.

$$d(l_j,GP)=\sum_{k=1}^{2}d(v_{kj},gp_k) \quad (17)$$

$$d(l_j,GN)=\sum_{k=1}^{2}d(v_{kj},gn_k) \quad (18)$$

$$GC(l_j)=\eta\frac{d(l_j,GP)}{d(l_j,GP)+d(l_j,GN)}+(1-\eta)\frac{d(l_j,GN)}{d(l_j,GP)+d(l_j,GN)} \quad (19)$$

where $\eta(0<\eta<1)$ is the subjective attitude of the group, which reflects the different importance of FPGIRP and FNGIRP. Therefore, the principle of choosing η is similar to that of μ.

Step 4: Calculate the mean value $s(GC(l_j))$ according to Eq. (1). The path corresponding to $\max_{1\le j\le 4}\{s(GC(l_j))\}$ is the optimal landing path in the current environment. Besides, the rank of alterative paths can be calculated at the meantime. Note that: the final decision has to be close to those of both decision makers.

4. Experimental study on landing path selection in different environments

In this section, experiments are conducted to investigate the effectiveness of the proposed path selection strategy. Four different environmental conditions are set as test scenarios to verify its reasonability. Under the known priori knowledge, experience, current environment evaluations and

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weights of decision makers, the path selection strategy is expected to choose the optimal landing path for the current environment.

4.1 Simulation conditions and their fuzzy descriptions

The performance ratings and environment evaluations are shown in Table 4.

Table 4. Expressions of performance ratings and environment evaluations

	Linguistic variables and expressions				
Performance ratings	NO	LO	ME	HI	VH
Environment evaluations	TP	LP	NO	GO	VG
Triangular membership function	[0,0,0.1]	[0.1,0.3,0.5]	[0.3,0.5,0.7]	[0.5,0.7,0.9]	[0.9,1,1]

Four pairs of simulations are carried out independently to validate the reasonably of the proposed method in different environments,. The environment settings and evaluations of decision makers are presented in Table 5 and Table 6.

Table 5. Environment settings

Serial number of simulation	Environments
i	The weather, clouds height and visibility are good while the performance of aircraft and air traffic situation are normal.
ii	The weather, clouds height and visibility are not good enough while the performance of aircraft and air traffic situation are good.
iii	The weather, clouds height and visibility are bad while the performance of aircraft and air traffic situation are good.
iv	The weather, clouds height and visibility are normal while the performance of aircraft and air traffic situation are bad.

Table 6. Environment evaluations of decision makers

Contributing factors		f_1	f_2	f_3	f_4	f_5
Simulation i	Pilot	VG	VG	VG	NO	NO
	LCO	GO	GO	GO	GO	GO
Simulation ii	Pilot	GO	GO	GO	GO	GO
	LCO	LP	LP	NO	GO	VG
Simulation iii	Pilot	TP	TP	TP	GO	GO
	LCO	TP	TP	TP	GO	VG
Simulation iv	Pilot	LP	LP	NO	NO	TP
	LCO	TP	NO	LP	NO	TP
Weight of decision maker	Pilot $\lambda_1 = [0.4, 0.5, 0.6]$ LCO $\lambda_2 = [0.8, 0.9, 1]$					

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4.2 Results and analyzes of landing path selection

The proposed landing path selection strategy is applied to determine the optimal landing path for four different validating environment conditions. The results are given in Table 7-10. For each test case, the optimal landing path and the ranking the four alterative paths are given.

Table 7. Results of simulation i

Alternative route	l_1	l_2	l_3	l_4
Closeness coefficient	[0,0.82,161.06]	[0,0.80,159.28]	[0,0.51,107.62]	[0,0.20,55.49]
Mean value	40.67	40.22	27.16	13.97
Rank	$l_1 > l_2 > l_3 > l_4$			
The optimal landing path	l_1			

Table 8. Results of simulation ii

Alternative route	l_1	l_2	l_3	l_4
Closeness coefficient	[0,0.74,87.00]	[0,0.80,88.11]	[0,0.58,61.20]	[0,0.20,31.48]
Mean value	22.12	22.43	15.59	7.97
Rank	$l_2 > l_1 > l_3 > l_4$			
The optimal landing path	l_2			

Table 9. Results of simulation iii

Alternative route	l_1	l_2	l_3	l_4
Closeness coefficient	[0,0.51,5.24]	[0,0.80,5.89]	[0,0.80,6.41]	[0,0.20,2.84]
Mean value	1.57	1.87	2.00	0.81
Rank	$l_3 > l_2 > l_1 > l_4$			
The optimal landing path	l_3			

Table 10. Results of simulation iv

Alternative route	l_1	l_2	l_3	l_4

Closeness coefficient	[0,0.20,6.47]	[0,0.21,6.50]	[0,0.47,7.23]	[0,0.80,6.79]
Mean value	1.72	1.73	2.04	2.09
Rank	$l_4 > l_3 > l_2 > l_1$			
The optimal landing path	l_4			

From Simulation i to Simulation iv, the environment condition set for each validation case is degrading gradually. With the changes of the environment setups, the path selection strategy is able to determine the optimal landing path for each validation case. Note that l_4 always ranks in the last place when the environment condition is generally good for the aircraft landing. It demonstrates that the pilot won't land the aircraft on the ground unless the situation is too bad. In general, the above results indicate that the proposed path selection strategy is able to describe and cope with the fuzziness of aircraft performance, environment and traffic situation. The optimal landing path under different environments can be obtained. The proposed path selection strategy can provide the pilot and the LCO with a useful tool to guide the aircraft landing safely. Besides, the workload of pilot and LCO is also reduced.

5. Conclusion

In this paper, the path selection problem for aircraft landing on the carrier is studied, and a new path selection strategy is developed to solve the problem. The goal is to improve the safety level of aircraft landing and reduce the workload of the pilot and the LCO at the same time. Firstly, the path selection problem associated with the aircraft landing problem is described. Secondly, essential elements involved in this problem are analyzed. Thirdly, a conceptual model that reflects the essence of solving the problem is drawn.

Using the fuzzy TOPSIS approach improved in this paper, the environmental information, the performance ratings and weights of decision makers are described using linguistic variables. By introducing linguistic variables, fuzziness in description and judgment can be solved. Subsequently, a mathematical model, which can evaluate the rationality of each alternative landing path for the current environment, is built. Finally, to compromise the judgements from different decision makers, the group decision-making approach is introduced, and the optimal landing path is obtained by taking into account the judgments of both the LCO and the human pilot. Experimental results under different environments indicate that the proposed landing path selection strategy has a good performance of making a quick and reasonable decision, thus the optimal landing path is obtained.

The landing selection strategy proposed in this paper can reduce the workload of the pilot and the LCO by determining the optimal landing path for the returning aircraft. The work of this paper belongs to one of the key technologies of automatic landing of carrier aircraft, and it is the first issue to be addressed in the whole process of landing. In the future, the design of automatic control law will be studied to track the landing path determined in this paper.

Conflicts of Interest: The authors declare no conflict of interest.

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