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A novel aircraft artificial fuzzy heuristic theory for nonlinear simulations

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Abstract. This paper presents a novel artificial fuzzy heuristic theory specifically designed for nonlinear simulations in the context of aircraft systems. Leveraging the principles of fuzzy logic, the proposed methodology addresses the complexities and uncertainties inherent in nonlinear dynamics of aircraft behavior. By integrating fuzzy inference systems with heuristic optimization techniques, we develop a robust framework that enhances the accuracy and efficiency of simulations. The study begins with a comprehensive review of existing methodologies in aircraft simulation, highlighting their limitations in handling nonlinearities and uncertainties. We then introduce our fuzzy heuristic approach, detailing its architecture and operational mechanisms. Through a series of simulations, we demonstrate the effectiveness of our theory in predicting aircraft performance under various operational scenarios. Results indicate significant improvements in simulation accuracy and computational efficiency compared to traditional methods. The proposed approach not only facilitates better understanding and analysis of aircraft dynamics but also provides a valuable tool for engineers and researchers in the field of aerospace engineering. Future work will explore the integration of this theory with real-time systems and its application in flight control design.

Keywords: aircraft systems; artificial intelligence; dynamics modeling; fuzzy logic; heuristic optimization; nonlinear simulations; performance prediction; simulation accuracy

1. Introduction

The dynamic behavior of aircraft is inherently complex, characterized by nonlinear interactions among various physical and environmental factors. As modern aircraft systems become increasingly sophisticated, the need for accurate simulation tools that can effectively model these complexities has never been more critical. Traditional simulation methods, often based on linear approximations, frequently fall short in capturing the intricate dynamics of aircraft performance, particularly under varying operational conditions (Smith *et al.* 2020). This limitation can lead to significant discrepancies between simulated outcomes and real-world performance, potentially compromising safety and efficiency in aerospace engineering.

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Recent advancements in artificial intelligence (AI) and fuzzy logic present promising alternatives for improving simulation accuracy. Fuzzy logic, introduced by Zadeh (1965), provides a framework for reasoning under uncertainty, allowing for more nuanced decision-making processes that can accommodate the vagaries of real-world scenarios. Its application in control systems and decision-making has demonstrated considerable success, yet its potential in enhancing nonlinear simulations within the aerospace sector remains largely untapped. The integration of fuzzy logic with heuristic optimization techniques offers a novel approach to tackle the challenges posed by nonlinear dynamics.

In this context, our research introduces a novel artificial fuzzy heuristic theory specifically designed for nonlinear simulations of aircraft systems. This approach combines the strengths of fuzzy inference systems with heuristic optimization methods, creating a robust framework capable of adapting to the complexities of aircraft dynamics. By utilizing fuzzy logic, our theory can effectively model the uncertainties and nonlinear behaviors that traditional methods often overlook. This is particularly crucial in scenarios where aircraft are subjected to extreme conditions, such as turbulence or rapid maneuvers, where accurate predictions are vital for safety and performance optimization.

The proposed methodology begins with the establishment of a fuzzy inference system that captures the essential characteristics of aircraft dynamics. By defining fuzzy sets and rules based on expert knowledge and empirical data, we can model the relationships between various input parameters and their effects on aircraft performance. This fuzzy framework allows for the incorporation of imprecise and uncertain information, which is often present in real-world scenarios (Mamdani and Assilian 1975). Subsequently, heuristic optimization techniques are applied to refine the simulation outputs, ensuring that the model not only reflects theoretical predictions but also aligns closely with observed data.

Preliminary results from our simulations indicate that the artificial fuzzy heuristic theory significantly improves the accuracy of nonlinear simulations compared to traditional methods. By conducting a series of comparative analyses, we demonstrate that our approach can effectively predict aircraft performance across a range of operational scenarios, thereby providing valuable insights for engineers and researchers in the field of aerospace engineering. The implications of this research extend beyond improved simulation accuracy; they also contribute to the development of more reliable aircraft design and control strategies.

As the aerospace industry continues to evolve, the integration of advanced computational techniques, such as our proposed fuzzy heuristic theory, will be essential in addressing the growing complexities of aircraft systems. Future work will focus on refining the methodology further and exploring its application in real-time systems, enhancing its utility in flight control design and operational decision-making. Ultimately, this research aims to bridge the gap between theoretical advancements in fuzzy logic and their practical applications in aerospace, paving the way for safer and more efficient aircraft operations.

2. System description

We consider a connected network $G=(\{0\} \cup N,A)$ underlying the problem. In $\{0\} \cup N$, node 0 represents the depot and N represents the set of demand nodes. A denotes the set of arcs in the network (direct road connections). For every pair i, j e $\{0\}$ U N, we assume that we can compute the cost for linking those nodes by road (e.g., based upon the shortest path between i and j and the per-unit distance transportation cost).

The following parameters defining our problem are considered:

m, number of vehicles for road delivery (vans);

d, number of drone stations;

p, maximum number of drone stations allowed;

f, fifixed cost of using the drone station;

cr_{ij}, traveling cost between nodes i and j ($i,j \in \{0\} \cup N$);

cd_i^k, transportation cost for satisfying node i by the drone from station k ($i \in N$, $k \in D$).

The problem can be mathematically formulated using the following sets of decision variables:

$$y^k = \begin{cases} 1, if\ drone\ station\ k\ is\ used; \\ 0, otherwise. \end{cases} \quad (k \in D)$$

$$s_i^k = \begin{cases} 1, \text{if node } i \text{ is served by the drone from station } k; \\ 0, \text{otherwise.} \end{cases} \quad (k \in D, i \in N)$$

$$z_i = \begin{cases} 1, \text{if node } i \text{ is served by road vehicle (van);} \\ 0, \text{otherwise.} \end{cases} \quad (i \in N)$$

$$x_{ij}^v = \begin{cases} 1, \text{if a road vehicle (van) travels directly from node } i \text{ to node } j \text{ by van } v; \\ 0, \text{otherwise.} \end{cases} \quad (i,j \in \{0\} \cup N)$$

We can finally present the following integer programing model for the mTSP-LAP

$$\min \sum_{i=1}^{n} \sum_{j=1}^{n} \left(\sum_{v=1}^{m} x_{ij}^v\right) \cdot cr_{ij} + \sum_{i=1}^{n} \sum_{k=1}^{K} s_i^k cd_i^k + \sum_{k=1}^{K} y^k \cdot f \tag{1}$$

$$\sum_{k=1}^{d} y^k \le p, \forall k \in D \tag{2}$$

$$s_i^k \le y^k, \forall \mathrm{i} \in \mathrm{N}, \mathrm{k} \in D \tag{3}$$

$$\sum_{k=1}^{d} s_i^k + z_i = 1, \forall i \in N \tag{4}$$

$$0 \le \sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{\mathrm{v}=1}^{\mathrm{m}} \mathrm{x}_{\mathrm{ij}}^{\mathrm{v}} = z_i, \forall j \in N \tag{5}$$

$$0 \le \sum_{\mathrm{j}=1}^{\mathrm{n}} \sum_{\mathrm{v}=1}^{\mathrm{m}} \mathrm{x}_{\mathrm{ij}}^{\mathrm{v}} = z_i, \forall i \in N \tag{6}$$

$$\sum_{\mathrm{j}=1}^{\mathrm{n}} \sum_{\mathrm{v}=1}^{\mathrm{m}} \mathrm{x}_{0\mathrm{j}}^{\mathrm{v}} = m \tag{7}$$

$$\sum_{\mathrm{i}=1}^{\mathrm{n}} \sum_{\mathrm{v}=1}^{\mathrm{m}} \mathrm{x}_{\mathrm{i}0}^{\mathrm{v}} = m \tag{8}$$

$$u_i - u_j + n \cdot \sum_{v=1}^{m} \mathrm{x}_{\mathrm{ij}}^{\mathrm{v}} \le n - 1, 1 \le i \ne j \le n \tag{9}$$

$$s_i^k \in \{0,1\}, \forall i \in N, \forall k \in D \tag{10}$$

$$x_{ij,}^v \in \{0,1\}, \forall j \in N \cup j = 0, \forall i \in N \cup i = 0 \tag{11}$$

$$y^k \in \{0,1\}, \forall k \in D \tag{12}$$

$$z_i \in \{0,1\}, \forall i \in N \tag{13}$$

The objective function (1) represents the total cost that includes (i) the cost of using drone stations; (ii) the transportation costs for the road delivery vehicles as well as for the drone-carrying truck; and (iii) the drone delivery cost. Because the construction of the station is a one-time cost, once the station is set up, its subsequent use, maintenance and other costs can be ignored. Therefore, we consider designing a fixed cost for the station. Constraint (2) represents the maximum number of drone stations allowed. Inequality (3) states that if a drone serves a demand node from one station then the station should be operating. Constraint (4) ensures that every demand node is served by exactly one and only one transportation mode (either by van or by drone). Constraint (5)-(6) means that it is only served by the van at both point *i* and point *j*, and there will be a path of van from *i* to *j*. Constraints (7)-(8) indicate that a total of *m* vans depart from the distribution center and return to the distribution center. Constraint (9) is an MTZ constraint, which ensures that there will be no sub-tours in the path of the vans. Constraints (3)-(6) ensure the synchronization of the vans' path planning with drone station selection and drone path planning. When planning the path of the vans, it is necessary to prevent the demand point being served by drone. When making drone distribution decisions, it is also necessary to prevent the demand points being served by vans. Finally, (10)-(13) define the domain of the decisions variables.

Remark 1. *The above* problem *contains a TSP as a particular case and thus it is NP-hard.*

Remark 2. *We can relax the* integrality *constraints on the x-variables as well as the upper bound, thus simply writing that*

$$s_i^k \geq 0, i \in N, k \in D.$$

In fact, it is easy to see that since the y-variables are integer, there is always one optimal solution such that the s-variables are also integer.

Remark 3. *In the above model, we include the fixed cost ofusing the drone station. However, in our algorithmic procedure to be proposed in the next section and when analyzing the results, we start by ignoring this component and use it last as part of a post-optimization analysis.*

Looking at the above model, we easily identify the "location-allocation" component, Constraints (2)-(3); the "mTSP" component, Constraints (5)-(9); and the linking constraints, Constraints (4)-(6). The hardness of the problem together with many data-driven *applications* in which upon collecting the data a solution must be found in a very short time justifies the development of a heuristic algorithm for the problem. In fact, in many real-world last-mile delivery applications (e.g., food delivery), customers expect to be satisfied shortly after calling to be served and thus we cannot afford waiting too long to obtain an optimal solution to the problem. Nevertheless, in Section 5, we reported on some results obtained by solving the above model with an off-the-shelf solver.

3. Algorithm design of adaptive large neighborhood search

Considering the solution constructed in the first phase, we denote by E a set of edges that will be analyzed in this phase to induce improvements in the solution. Initially, this set contains all the direct road links used by the solution. We denote by C_{incumb} the current solution cost. We also define a set *T* containing all the demand nodes served by a road tour, which is of course equal to *N* when we start this improvement phase.

Our procedure iteratively attempts to remove nodes from *T* when a demand node is scheduled to be served by the drone. This is accomplished by selecting the edge

$$\{j^*, \ell^*\} = \begin{matrix} \arg\min\{c_{j\ell}\} \\ \{j, \ell \in E\} \end{matrix}$$

and (separately) computing saved cost among the total delivery cost (road and air) from servicing

j^* or $\ell^*$with the drone (from the closest drone station to each node). We denote by $C_{j^*}$the total delivery cost if j^* is served by air (the Hamiltonian tour for the depot and cluster j^* belongs to is also recomputed—using nearest-neighborhood computation as before). Similarly, we compute C_{ℓ^*}. Finally, we have the savings:

$$\Delta C_{j^*} = C_{incumb} - C_{j^*},$$

and:

$$\Delta C_{\ell^*} = C_{incumb} - C_{\ell^*},$$

Now, we distinguish three cases for deciding the course of action to take:

Case 1: $\Delta C_{j^*} > \Delta C_{\ell^*}$ and $\Delta C_{j^*} >0$.

In this case, demand node j* is removed from *T* since it will be served by the drone (from the closest drone station).

Case 2: $\Delta C_{\ell^*} > \Delta C_{j^*}$ and $\Delta C_{\ell^*} > 0$.

In this case, demand node is removed from *T* since it will be served by the drone (from the closest drone station).

Case 3: $\Delta C_{j^*} < 0$ and $\Delta C_{\ell^*} < 0$.

In this case, nodes j^* andremain in the initially established road route and the corresponding edge $\{j^*,\ell^*\}$ is removed from the set of edges (*E*) to be analyzed.

The improvement phase just described is formally detailed in Algorithm 1. In this algorithm, Γ(.) denotes the cluster to which a node belongs to.

4. Fuzzy advanced NN propagation

Let the output of the first layer of neuron be the input of the next layer of neuron. DNN MLP works like this: neurons in the input layer receive a signal, add weights, process it and send it to a transfer function. output. These results are sent to neurons in the first hidden layer. Here the neuron receives the input signal. Process those signals and send the results to other hidden layers. This process continues until neurons in the output layer produce an output.

DNN preliminary details are described as follows.

1. An input of iterations is k.
2. start b_{ij}={deviation}, w_{ij}=0
3. when iteration number ≤k
4. jobs w_{ij} (weight of applicants)=0
5. Update the hidden layer weights and input weights: $a_{ij}=\sigma(w_{1j}\,x_{1j}+ w_{2j}\,x_{2j}+\ldots+ w_{ij}\,x_{ij})$ where j is the jth hidden layer.
6. Use dropouts to reduce the chance of overfitting.
7. count outputs $y_i = \frac{\exp(a_{ij})}{\sum_{i=1}^{n}\exp(a_{ij})}$
8. Calculate the cost function $C = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2$

Adjust the weight Δ $G_F=-\eta\times C=w_{ij}$ according to the gradient error w_{ij}

10. update weights and biases
11. ended

Deep learning allows the learning of computational models and involves multiple layers of processing with multiple levels of data abstraction. Deep learning algorithms mimic the biological nervous system in sending messages to identify targets. In the biological nervous system, neurons are interconnected. The architecture of the network is shown in Fig. 1, and the algorithm is given a DNN pseudo code.

$$\begin{gathered} a_{ij} = \sigma(A_{ij}) = \frac{1}{1+ e^{-x_i}} \\ s.t. A_{ij} = b_{ij} + \textstyle\sum_i x_{ij} w_{ij} \end{gathered} \tag{1}$$

where b_{ij} the bias unit i, j is the layer index below the considered layer and w_{ij} is the connection weight. x_{ij} Output unit for time series forecasting a_{ij} between and within considered layers It x_{ij+1} uses y_i “softmax” nonlinearity to transform input sums x_{ij}

$$y_i = \frac{\exp(a_{ij})}{\sum_{i=1}^{n} \exp(a_{ij})} \tag{2}$$

DNNs can perform discriminative training by backpropagating the derivative of a cost function that measures the difference between the target result and the actual result produced for each training case. Using the softmax output function, the cost function C is the cross entropy between the actual and predicted values, which is given by

$$C = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y_i})^2 \tag{3}$$

Where y_i the i-th predicted value $\hat{y_i}$ is the i-th actual value.

It is often more efficient to calculate the derivatives of “subsets” of the training cases in the training set before calculating the slope-based weights for the larger training set. Adam’s optimization algorithm is used to update the network weights on the inverse training data to suppress the swing and accelerate the downhill.

The most recent information is given the highest weight. Older data is given less weight. And give a simple method to calculate the forecast range

$$S_t = a \cdot y_t + (1 - a) S_{t-1} \tag{4}$$

where S_t the smoothed value mean y_t of the sums S_{t-1}.

a and S_{t-1} a can be determined S_t when y_t a=1, S_t=y_t. Newer values are given higher weight. And the new values have a large effect on the current values. This multiplication process continues until 1.

$$A_t = w_1 A_{t-1} + w_2 A_{t-2} + w_3 A_{t-3} + \cdots + w_n A_{t-n} \tag{5}$$

Furthermore, more recent information is given more weight than previous information.

$$v_t = \beta v_{t-1} + (1 - \beta) \theta_t \tag{6}$$

In formula (6) θ_t is the actual value at time t, the coefficient β is the rate at which the weight index decreases. (The lower the coefficient, the faster the value will decrease) and this v_t is the forecast value at time t, i.e., the EWMA for keeping the series constant. Accessing the underlying data requires sequence integration. (for continuous sequences) or compute the variances of all sequences (for continuous sequences). The ARIMA forecast equation for a stationary time series is a linear equation (i.e., regression), and the forecast variables include the lag and error of the dependent variable. In forecasting, non-seasonal ARIMA models are classified as “ARIMA (p, d,

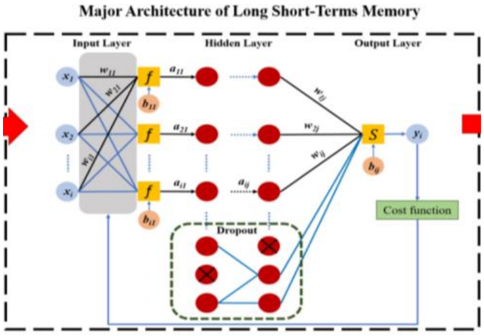


Fig. 1 Multi-layer artificial neural network recognition model

q)”. The forecast equations are therefore the basic process that creates the time series as follows.

$$\begin{aligned} y_t = {} & \theta_0 + \varphi_1 y_{t-1} + \varphi_2 y_{t-2} + \cdots + \varphi_p y_{t-p} \\ & + \varepsilon_t - \theta_1 \varepsilon_{t-1} - \theta_2 \varepsilon_{t-2} - \cdots - \theta_q \varepsilon_{t-q} \end{aligned} \tag{7}$$

Here y_t and ε_t are the exact values and random errors at time *t*, respectively φ_i(i=1, 2,…,*p*) and θ_j(*j*=0, 1, 2,…,*q*) are the model parameters. Also, *p* and *q* are integers which are often called the model sequence. Assume that the random errors (ε_t) are independent and uniformly distributed. with zero mean and variance. σ_2

An extended version of the BPN architecture has an L-layer network with forward-connected processors. Each input layer node ($z_1, z_2, \dots,$) $h_1^{(1)}$ is connected to each node of the first hidden layer (z_P, $h_2^{(1)}$, ...,), $h_{Q1}^{(1)}$ then the first hidden layer node $h_1^{(2)}$ is connected to the next hidden layer node (, $h_2^{(2)}$, ...,). $h_{Q1}^{(2)}$ And the process continues. until the last hidden layer node ($h_1^{(L-1)}$, $h_2^{(L-1)}$, ..., $h_{Q_{L-1}}^{(L-1)}$) is connected to the output layer node ( ) $\hat{y}_t$ where *l*=1, ...,*L*. The above structure is stated as follows

$$h_j^{(1)} = g^{(1)}\left(\sum_{i=1}^{(p)} w_{i,j}^{(1)} z_i + w_{0,j}^{(1)}\right) \tag{8}$$

$$h_j^{(l)} = g^{(l)}\left(\sum_{i=1}^{(Q_{l-1})} w_{k,j}^{(l)} h_k^{(l-1)} + w_{0,j}^{(l)}\right) \tag{9}$$

$$\hat{y}_t = h_j^{(L)} = g^{(L)}\left(\sum_{i=1}^{(Q_{l-1})} w_{k,j}^{(l)} h_k^{(l-1)} + w_{0,j}^{(l)}\right) \tag{10}$$

The approximate value is where $\hat{y}$ the input data z_i can respond to external variables at time *t* or lag. and the remaining exogenous variables at time *t* or lag, where (*i*=1,…,*p*) denotes the weights from node *k* to node *j* at the lth layer (*l*=1,…, *L*, *k*=1,…, *p*). $w_{k,j}^{(l)}$, and *j*=1, …,, Q_l where Q_l the layer number of neurons in l) $h_j^{(l)}$ is the output of neuron *j* in layer *l* (*l*=1, …,*L* and *j*=1, …, Q_l is the number of neurons in layer *l*. Q_l) $w_{0,j}^{(l)}$ and layer *l* represents the weight of node *j*. The bias unit (*l*=1,…,*L* and *j*=1,…, Q_l) $g^{(l)}$ represents the transfer function at layer *l*. 8) Prediction Performance Standard: Mean Square Error. Root (RMSE) and absolute percentage error (MAPE) are commonly used statistical methods to compare the deviation between actual and predicted values. To evaluate the performance of DNN on prediction results.

5. Algorithm

The overall design process can be summarized as the following algorithm.

Step 1: The following formula shows how TNFN is created.

$$TNFN_i = \{Ind_{1Sel_1}, Ind_{2Sel_2}, \dots Ind_{RSel_R}\}, \tag{5.1}$$

where *i* is the number of selections and *TNFNi* is the *i*-th generated *TNFN*. Ind represents the individuals selected to create the *TNFN* and *Sel* represents the number of individuals selected in the *j*th subpopulation.

Step 2: The fitness program evaluates each *TNFN* prepared from step 1 to obtain a fitness value. Capacitance values are most commonly used to characterize the performance of each *TNFN*. In short, the use of value is an important development process as it plays a key role in determining whether we find the best solution. The value of ability to conceive may help individuals make more appropriate and adaptive assessments. In this study, we evaluated the performance of TNFN using the well-known mean squared error (*RMS*) (Reyes *et al.* 2010). This is because it can more accurately reflect the model's performance. formula. (5.2) represents the fitness function developed in this study.

$$Fitness\,Value = \frac{1}{\left(\sqrt{\frac{\sum_{i=1}^{n}\left(x_i - x_i'\right)^2}{n}} + 1\right)}, \tag{5.2}$$

where x'_i Represents *TNFN* releases and releases with bugs. It can be seen from the formula (5.2) refers to higher fitness values. This means that *TNFN* release is closer to the output and vice versa.

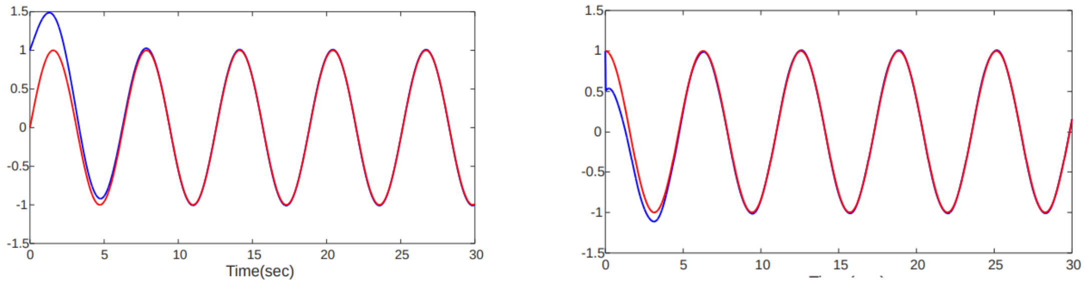
Step 3: After obtaining the fitness value for each selected *TNFN*, the fitness program uses the *TNFN* to calculate the fitness value for each individual. Specifically, divide the fitness value obtained in step 2 by the number of moments (that is, *R*). The selected individual's shared talent ratio is then accumulated. We're talking about the values chosen when collecting the overall probability of solving the task to make sure each individual is on the other link. This is primarily used to prevent holistic solutions from working for poor performance problems due to the number of underperforming individuals. This keeps the individual's optimal mix.

Step 4: In the last step, each character's cumulative value is divided by the number of times that character was selected. Average capacity then represents the cost of an individual system. formula. (5.3) shows the calculation of the average fitness value.

$$Fitness\,Value_{Ind_{ij}} = Fitness\,Value_{Ind_{ij}} / Select\,Times_{Ind_{ij}}, \tag{5.3}$$

Where
$i = 1,2, \dots R,$
$j = 1,2, \dots SP_{size}.$
$Select\,Times_{Ind_{ij}}$ means the number of times Ind_{ij} has been selected.

In summary, the proposed AEA helps resolve different evaluation criteria for individuals in each subgroup. More specifically, cross-processing and transformation criteria can be considered. Therefore, not only can the developed sequence search a large search space if the solution deviates



(a) (b)

Fig. 2 Schematic diagram of calculation example generation

from the optimal solution, but it can also reduce the search space searched by the development if the solution and the optimal solution are close. AEA can therefore provide a powerful method for subgroup analysis.

6. Example

In order to verify the validity of the problem model and algorithm, the article has done the following two parts of experiments: (1) Comparing the solution results of 18 small-scale calculation examples of CPLEX and ALNS algorithms, it proves the validity of the model and algorithm; (2) Using The ALNS algorithm solves the medium-scale calculation example with 50 requirements and the large-scale calculation example with 100 requirements, verifies the stability of ALNS in solving large-scale problems, and analyzes the impact of the joint distribution mode of trucks and UAVs on path costs.

There is no ready-made calculation example for the PDPTW-D problem studied in this article, three types of calculations of cluster distribution C, random distribution R and random cluster distribution RC are generated based on the examples of Sacramento and Li. The example is used as the test case of the article. The location and demand of customer points in the calculation example. Fig. 2 is a schematic diagram of calculation example generation, (a) is a schematic diagram of VRP-D, (b) is a PDPTW-D after pairing of pick-up and delivery nodes and adding a time window schematic diagram. In Fig. 2, the square symbol represents the distribution center, the circle symbol represents the delivery point, the triangle symbol represents the pick-up point, the number above the symbol in figure (a) represents the demand, and the number (n, m, t) represent the demand, the lower limit of the time window and the upper limit of the time window, respectively.

Test environment and parameter settings

The computer configuration of the experiment is Intel Core I 5-7200U 2.5 GHz, 4 GB memory, ALNS is written in C++ language, IDE adopts Visio Studio 2019 and CPLEX adopts the default setting of CPLEX12.8.

ALNS in the article are set as follows: the total number of iterations is 15000, the maximum number of unimproved iterations is 2000, and the operator weight update criterion parameters $\sigma 1=33$, $\sigma 2=9$, $\sigma 3=13$. Simulated annealing temperature cooling rate $a=0.99975$.

Due to the excessive constraints and parameters of the model, even the small-scale calculation

Table 1 The solution results of small-scale calculation examples

AC	CPLEX				ALNS		
lc15-2	2	438.91	712.81	2	438.91	2.01	0
lr15-1	3	399.22	3600	3	333.88	4.48	-16.37
lr15-2	4	386.30	3600	4	333.37	2.74	-13.70
lrc15-1	4	432.55	3600	4	420.89	3.08	-2.70
lrc15-2	5	568.31	3600	5	531.19	2.38	-6.53
lc20-1	2	454.85	3600	2	461.58	3.42	1.48
lc20-2	2	431.81	3600	2	431.68	4.57	-0.03
lr20-1	5	678.82	3600	5	548.76	3.67	-19.16
lr20-2	5	581.00	3600	5	470.31	5.19	-19.05
lrc20-1	7	1043.94	3600	7	847.77	3.64	-18.79
lrc20-2	7	956.86	3600	7	779.44	4.46	-18.54

example CPLEX solver cannot solve all of them accurately, some calculation examples cannot obtain the optimal solution within a limited time, and the improvement of the solution after 3600 seconds is small, so The article limits the maximum running time of CPLEX to 3600 seconds, and verifies the effectiveness of the ALNS algorithm by comparing the solution results of CPLEX within 3600 seconds and the solution results of ALNS. In Table 1 to Table 3, AC represents the name of the calculation example, RN represents the number of paths, TC represents the total cost, RT represents the running time, Gap represents the deviation between the solution result of the ALNS algorithm and the solution result of CPLEX, and its value is (TC(ALNS)-TC(CPLEX))/TC(CPLEX).

18 small-scale calculation examples solved by CPLEX and ALNS are shown in Table 1. The bold font indicates the better running results of the two solution methods, and the negative Gap indicates that the solution effect of the ALNS algorithm is better than that of CPLEX. From the results, there are 11 cases where the ALNS results are better than the CPLEX results, and the cost difference is up to 19.16%; there are 6 cases where the ALNS results are the same as the CPLEX results; only 1 case has the ALNS results Slightly worse than CPLEX. From the solution time point of view, the running time of ALNS is less than that of CPLEX. However, it is difficult for CPLEX to obtain the optimal solution for 20 requirements within 3600 seconds, while ALNS can obtain an accepted and effective solution within 5 seconds, which shows that the problem model proposed in the article and the ALNS algorithm are very effective for “truck + UAV”. Pick-up and delivery path planning in mode is effective.

In order to verify the stability of the ALNS algorithm for medium-scale and large-scale calculation examples, and analyze the impact of the joint distribution mode of trucks and drones on the route cost, the article analyzed three different types of type C, type R, and type RC, and 18 groups of 50 and 100 requirements are tested, and the calculation results are shown in Table 2 and Table 3.

In Table 2 and Table 3, Z IN Indicates the path cost of the initial solution in the joint distribution mode of trucks and UAVs, Z PDPTW Indicates the path cost for truck- only deliveries, Z PDPTW-D Indicates the path cost of the final solution in the joint distribution mode of trucks and UAVs, GAPI means and Z IN Compared to Z PDPTW-D Saved path cost, its value

Table 2 Solution results of 50 groups of customer points

AC	Z PDPTW	Z IN	Z PDPTW-D	GAPI(%)	GAPD(%)
lc5_1	306.96	334.79	213.59	36.2	30.42
lc5_2	308.87	253.33	238.15	5.99	22.90
lc5_3	533.63	432.75	351.61	18.75	34.11
lc5_4	509.11	401.22	388.98	3.05	23.60
lc5_5	660.95	635.40	451.76	28.90	31.65
lc5_6	680.31	750.74	485.96	35.27	28.57
lr5_1	328.28	311.25	245.80	21.03	25.12
lr5_2	325.13	351.33	298.02	15.17	8.34
lr5_3	589.74	405.46	303.30	25.20	48.57
lr5_4	592.27	508.03	401.97	20.88	32.13
lr5_5	662.28	706.03	523.64	25.83	20.93
lr5_6	689.47	878.76	634.85	27.76	7.92
lrc5_1	324.99	289.89	267.58	7.70	17.67
lrc5_2	324.92	302.05	262.41	13.12	19.24
lrc5_3	586.11	426.83	359.71	15.73	38.63
lrc5_4	573.41	537.83	394.73	26.61	31.16
lrc5_5	673.99	744.16	482.48	35.16	28.41
lrc5_6	654.64	641.31	581.38	9.34	11.19

Table 3 Solution results of 100 groups of customer points

AC	Z PDPTW	Z IN	Z PDPTW-D	GAPI(%)	GAPD(%)
lc10_1	618.79	484.32	318.85	34.17	48.47
lc10_2	625.86	469.37	382.40	18.53	38.90
lc10_3	849.94	831.39	536.26	35.5	36.91
lc10_4	881.86	531.23	529.49	0.33	39.96
lc10_5	1303.36	1354.55	939.58	30.64	27.91
lc10_6	1270.10	1198.80	1095.59	8.61	13.74
lr10_1	653.58	503.07	408.28	18.84	37.53
lr10_2	629.12	503.91	437.12	13.25	30.52
lr10_3	1004.71	954.70	775.77	18.74	22.79
lr10_4	964.50	695.96	494.30	28.98	48.75
lr10_5	1348.08	1217.99	936.20	23.14	30.55
lr10_6	1310.74	1222.66	1091.43	10.73	16.73
lrc10_1	650.91	440.29	419.38	4.75	35.57
lrc10_2	625.76	572.70	420.67	26.55	32.77
lrc10_3	965.61	772.57	543.80	29.61	43.68
lrc10_4	936.99	784.86	725.66	7.54	22.55
lrc10_5	1371.91	1257.49	961.66	23.53	29.90
lrc10_6	1354.43	1096.57	1017.47	7.21	24.88

is (Z IN -Z PDPTW-D) / Z IN, GAPD is expressed with Z PDPTW Compared to Z PDPTW-D The path cost saved is (Z PDPTW-Z PDPTW-D)/Z PDPTW.

It can be seen from Table 2 that the GAPI and GAPD values of the three different types of data of R, C and RC are greater than 0. The ALNS algorithm improves the initial solution by 15%-30%, and the initial solution is increased by 36.20% at the highest, indicating that ALNS can avoid local optimum and obtain a better solution; the joint distribution mode of trucks and drones saves path costs 15%-35%, the highest saving is 48.57%, indicating that the joint distribution of trucks and drones can save a lot of path costs compared with pure truck distribution, and the effectiveness and necessity of drones for medium-scale PDPTW problems.

From Table 3, it can be seen in R class, C class, RC Three different types of data are derived from GAPI and GAPD Values greater than 0, ALNS

Improve the initial solution by about 5%-30%, ALNS The highest improvement of the initial solution is 34.17%, indicating that ALNS In avoiding local optima and obtaining better.

The effectiveness of the solution; the joint distribution of trucks and drones saves 20%-40% of the path cost, and the maximum savings is 48.75%, indicating that the joint distribution of trucks and drones can save a lot of route costs compared with pure truck distribution, the effectiveness and necessity of UAVs for large-scale PDPTW problems.

By testing and solving three different types of medium-scale and large-scale calculation examples of type C, type R, and type RC, it can be seen that the ALNS algorithm improves the initial solution by about 15%-30%, and the performance of the algorithm is relatively stable. ALNS can Avoid local optima and obtain a better solution; the joint distribution of trucks and UAVs saves about 20%-35% of the path cost, indicating that the “truck+UAV” transportation mode can save a lot of path costs. In PDPTW In the problem, using the “truck+UAV” transportation mode can solve different types and different scales of calculation examples, and provide decision-making basis for the path planning of the actual “truck + UAV” mode for picking and delivering goods.

7. Conclusions

This research presents a novel artificial fuzzy heuristic theory aimed at enhancing the accuracy and reliability of nonlinear simulations in aircraft systems. As the aerospace industry faces increasing demands for sophisticated modeling techniques that can accommodate the complexities of modern aircraft dynamics, our proposed methodology offers a significant advancement over traditional simulation approaches. By integrating fuzzy logic with heuristic optimization techniques, we have developed a framework that effectively captures the nonlinear behaviors and uncertainties that characterize aircraft performance in real-world scenarios. The findings from our simulations demonstrate that the artificial fuzzy heuristic theory significantly improves predictive accuracy compared to conventional linear models. Through a series of comparative analyses, we have shown that our approach not only aligns closely with empirical data but also provides valuable insights into the underlying dynamics of aircraft behavior. This is particularly important in the context of safety-critical applications, where accurate predictions can inform design choices and operational strategies. The ability to model uncertainties and nonlinearities more effectively allows engineers to make better-informed decisions, ultimately enhancing the safety and efficiency of aircraft operations. One of the key strengths of our methodology is its adaptability. The fuzzy inference system employed in our framework can incorporate expert knowledge and empirical observations, allowing for a more nuanced understanding of aircraft dynamics. This flexibility is crucial, as it enables the model to evolve in response to new data and changing operational conditions. Furthermore, the heuristic optimization techniques applied in conjunction with fuzzy logic ensure that the simulation outputs are not only theoretically sound but also practically relevant. This dual focus on theoretical rigor and practical applicability positions our research as a valuable contribution to the field of aerospace engineering. The implications of this research extend beyond improved simulation accuracy. By providing a more reliable tool for modeling aircraft dynamics, our artificial fuzzy heuristic theory can facilitate advancements in various aspects of aerospace engineering, including design optimization, flight control, and performance evaluation. As the industry continues to embrace digital transformation and advanced computational techniques, the integration of our proposed methodology could lead to significant improvements in aircraft design processes and operational efficiency. Looking ahead, several avenues for future research emerge from our findings. First, further refinement of the fuzzy inference system and heuristic optimization techniques could enhance the robustness and accuracy of the model. Investigating the application of machine learning algorithms in conjunction with our fuzzy heuristic theory may also yield promising results, allowing for even greater adaptability and predictive capability. Additionally, exploring the integration of real-time data into the simulation process could provide insights into dynamic operational environments, further enhancing the utility of our approach in practical applications. In conclusion, the development of the artificial fuzzy heuristic theory represents a significant step forward in the modeling of nonlinear aircraft dynamics. By addressing the limitations of traditional simulation methods, our research contributes to the ongoing evolution of aerospace engineering practices. As the industry continues to face new challenges and complexities, the adoption of advanced computational techniques such as our proposed methodology will be essential in ensuring the safety, efficiency, and reliability of future aircraft systems. We believe that this research lays the groundwork for further exploration and innovation in the field, ultimately contributing to the advancement of aerospace technology and the enhancement of flight safety.

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