

## Research Article

# Research on Trajectory Planning in Thunderstorm Weather Based on Dynamic Window Algorithm during Approach Segment

Li Lu  and Chenyu Liu 

*School of Air Traffic Management, Civil Aviation Flight University of China, Sichuan, Guanghan 618307, China*

Correspondence should be addressed to Li Lu; 421361599@qq.com

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Dynamic window algorithm (DWA) is a local path-planning algorithm, which can be used for obstacle avoidance through speed selection and obtain the optimal path, but the algorithm mainly plans the path for fixed obstacles. Based on DWA algorithm, this paper proposes an improved DWA algorithm based on space-time correlation, namely, space-time dynamic window approach. In SDWA algorithm, a DWA associated with obstacle position and time is proposed to achieve the purpose of path planning for moving obstacles. Then, by setting the coordinates of the initial moving obstacle and identifying safety distance, we can define the shape of the obstacle and the path planning of the approach segment in thunderstorm weather based on the SDWA model was realized. Finally, the superior performance of the model was verified by setting moving obstacles for path planning and selecting the aircraft approach segment in actual thunderstorm weather. The results showed that SDWA has good path-planning performance in a dynamic environment. Its path-planning results were very similar to an actual aircraft performing thunderstorm-avoidance maneuvers, but with more smooth and economical trajectory. The proposed SDWA model had great decision-making potential for approach segment planning in thunderstorm weather.

## 1. Introduction

To ensure the flight safety of the aircraft, the path planning of the approach segment in thunderstorm weather is mainly to reasonably design the diversion route for aircrafts that may encounter thunderstorms on future route within a defined period of time. During approach, the aircraft's altitude decreases and is susceptible to thunderstorm hazards [1–5]. Thunderstorms produce violent updrafts and downdrafts; flying into it will cause serious damage to the aircraft. There is a large amount of super cooled water in the thunderstorm, which can result in icing on the exterior and thus hinders aircraft landing. Meanwhile, air collision will produce electric shock that can damage the protruding parts of the fuselage and electronic equipment [6, 7]. Therefore, how to effectively plan the path in thunderstorm weather is of great significance [8, 9].

Path planning is widely used in engineering. In the past few decades, a variety of path-planning models have been

proposed according to different angles. Path planning for fixed obstacles includes intelligent algorithm path planning, such as ant colony algorithm [10–13], traditional path-planning algorithms, such as artificial potential field method [14–16], and hybrid path-planning algorithms, such as potential field ant colony fusion method [17], Genetic fuzzy algorithm [18], and fuzzy neural network algorithm [19]. Path planning of moving obstacles includes Jiang Zhongyu's "Improved dynamic  $\alpha$  algorithm combined with time window" [20], Wu Chuanjun's "moving obstacle path planning based on dynamic spatiotemporal environment impact model and grid" [21], and Chen Jinfeng's "artificial potential field method combined with rolling window" [22]. For the approach segment path planning in civil aviation thunderstorm weather, the traditional algorithm [23, 24] is mainly used to plan the path of aircraft with thunderstorm on the route.

The dynamic window approach is a path-planning algorithm that drives objects by simulating trajectories at

different speeds, evaluating the trajectories, and selecting the speed under the optimal trajectory in the current window [25]. It can deal with a series of obstacle avoidance problems of fixed obstacles. In recent years, people have proposed a series of variants of DWA algorithm, such as DWA algorithm [26–28] combined with a  $\times$  algorithm, which has good application effects in solving path-planning problems in complex environments.

Due to the fixed height of the aircraft in the approach segment, a problem concerning the diversion path of the approach segment in thunderstorm weather is in fact a path-planning problem. However, thunderstorms are often dynamically unpredictable; using the traditional DWA algorithm is merely insufficient. Therefore, this paper designs a Dynamic Window Algorithm (SDWA) for path planning of moving obstacles through polynomial fitting of obstacle positioning and time in a single window, so as to efficiently and timely plan the diversion path in advance for thunderstorms that will appear on the route. As an example, the effectiveness of the algorithm is verified by taking the diversion of approach segment under actual thunderstorm weather at Taipei Taoyuan Airport.

## 2. The Establishment and Simulation of the Model

*2.1. Establishment of SDWA.* SDWA algorithm mainly includes the establishment of aircraft motion model and dynamic obstacle environment. The main process is shown in Figure 1.

### 2.1.1. Establishment of the Aircraft Motion Model

*(1) Establishment of Aircraft Motion Equation.* Due to the limitation of flight procedure, the aircraft cannot escape the protected area of the flight route. However, in the departure and arrival segments, the flight altitude is relatively low and can be easily affected by thunderstorm weather, forcing the aircraft to reroute. Therefore, this paper focuses on how to obtain the predicted flight trajectory before an aircraft encountering a thunderstorm.

In the approach segment, the aircraft has strict requirements on the altitude of rise and descend adjustments. Therefore, the diversion measures for thunderstorm clouds in the approach segment are mainly fly-around-motion [29]:

$$V_t = (v_t, w_t), \quad (1)$$

where  $v_t$  is the linear velocity of the aircraft at time  $t$  and  $w_t$  is the angular velocity of the aircraft. The aircraft trajectory is described, as shown in Figure 2:

When the distance between two adjacent moments is small enough, the trajectory can be regarded as a straight-line flight:

$$\begin{cases} \Delta x = v_t \Delta t \cos(\alpha_t), \\ \Delta y = v_t \Delta t \sin(\alpha_t). \end{cases} \quad (2)$$

Therefore, the coordinates of the aircraft at a certain time (i.e., the accumulation of the previous displacements) and the yaw angle of the aircraft can be expressed as

$$\begin{cases} x_{t+1} = x_t + v_t \Delta t \cos(\alpha_t), \\ y_{t+1} = y_t + v_t \Delta t \sin(\alpha_t), \\ \alpha_{t+1} = \alpha_t + w_t \Delta t. \end{cases} \quad (3)$$

*(2) Aircraft Motion parameters.* There are infinite groups of velocities in two-dimensional space; due to the influence of aircraft itself and the thunderstorm, the velocity can be constrained by the following restrictions:

- (1) Speed limit under self-performance guarantee:

$$v_t = \{v \in [v_{\min}, v_{\max}], w \in [w_{\min}, w_{\max}]\}. \quad (4)$$

- (2) Aircraft is limited by its own engine performance:

$$V_t \left\{ (v, w) \mid \begin{array}{l} v \in [v_{t-1} - v_a \Delta t, v_{t-1} + v_b \Delta t] \\ \cap w \in [w_{t-1} - w_a \Delta t, w_{t-1} + w_b \Delta t] \end{array} \right\}, \quad (5)$$

where  $v_a$  and  $w_a$  are the maximum braking linear acceleration and angular acceleration that the aircraft can provide at  $t-1$  and  $v_b$  and  $w_b$  are the maximum driving linear acceleration and angular acceleration of the aircraft at  $t-1$ .

- (3) Based on the distance limit between the aircraft and the thunderstorm.

In order to avoid the thunderstorm during the approach segment, the aircraft will decelerate with the maximum braking acceleration:

$$\begin{cases} V_t^2 = \left\{ (v^2, w^2) \left[ \begin{array}{l} v^2 \leq 2v_a D(v_{t-1}, w_{t-1}) \\ \cap w^2 \leq 2w_a D(v_{t-1}, w_{t-1}) \end{array} \right] \right\}, \\ V_t \geq 0 \end{cases} \quad (6)$$

where  $D$  is the minimum distance between the aircraft and the thunderstorm at  $t-1$ .

- (3) Aircraft speed evaluation function.*

- (1) Establishment of evaluation function index: the speed evaluation index of aircraft is mainly determined by three indexes, as shown in Table 1.
- (2) Normalization of indicators: since the three indexes are of different dimensions, they are normalized [30] as follows:

$$x(i) = \frac{x(i)}{\sum_{i=1}^k x(i)}. \quad (7)$$

$x(i)$  is the  $x$  index of  $i$  trajectories in the current dynamic window algorithm [31] and  $k$  is all trajectories in the current dynamic window.

- (3) Speed evaluation function.

Based on the existing evaluation index, the proportion is set to establish a comprehensive evaluation function:

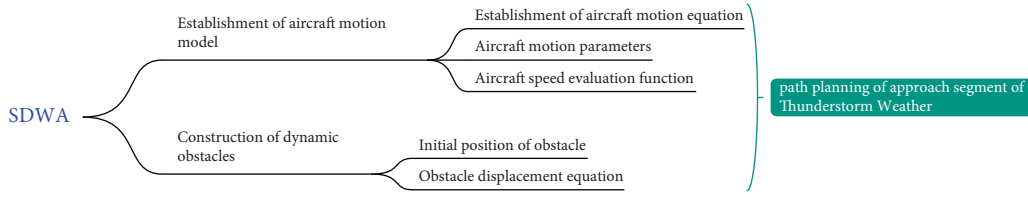


FIGURE 1: The flow of SDWA.

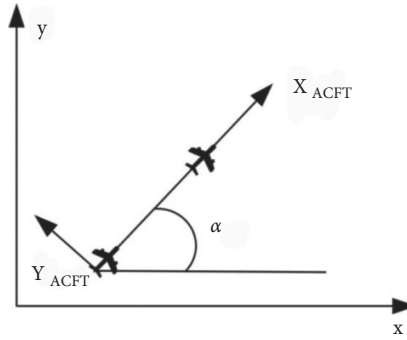


FIGURE 2: Aircraft flight model diagram.

TABLE 1: Flight speed evaluation index table.

Heading angle	$A(v, w) = \pi - \theta$ ( $\theta$ is the angle between the current course of the aircraft and the target direction)
Distance from thunderstorm	$D(v, w)$
Speed	$V(v, w)$

$$H(v, w) = \beta A + \gamma D + \varepsilon V. \quad (8)$$

Among  $\beta$ ,  $\gamma$ , and  $\varepsilon$ , in this paper, the safety distance from thunderstorm cloud is the main evaluation index  $\beta = 0.3, \gamma = 0.4$ , and  $\varepsilon = 0.3$ .

### 2.1.2. Setting of Dynamic Obstacles

(1) *Setting of Initial Position of Obstacle.* When the aircraft arrives at the approach segment, the location of thunderstorm can be described as follows:

$$P = (x, y). \quad (9)$$

(2) *Obstacle Moving Trajectory Equation.* After the aircraft arrives at the approach segment, the moving trajectory of obstacles can be described by establishing the trajectory equation related to  $t$ , and the trajectory equation is as follows:

$$\begin{cases} x = f(t), \\ y = g(t). \end{cases} \quad (10)$$

2.2. *Matlab Model Simulation.* According to the established aircraft motion model, Matlab is used for simulation [32] to observe whether the predicted route of the aircraft to avoid

thunderstorm is reasonable. Here, the shape of thunderstorm is set as a round thunderstorm with a circular trajectory (that is, moving obstacles are composed of four adjacent points in the simulation process). The specific algorithm flow is shown in Figure 3, and the parameters are shown in Table 2.

The simulation results are shown in Figure 4.

It can be seen from Figure 4 that the thunderstorm moves in a circular area with (2, 2.5) as the center and 50 km as the radius. The aircraft flies at the initial heading angle  $\pi/4$ . The model was successfully used to avoid the moving thunderstorm, which verified the feasibility of the model and compared with other path-planning algorithms in dynamic environment; this method makes use of the dynamic characteristics of DWA, and the algorithm has fast solution speed and high efficiency.

## 3. Flight Example Verification

To verify the reliability of the model, this paper takes the BR721 flight on PVG-TPE of TPE approach segment on June 6, 2021, as an example, as shown in Figure 5.

In the picture, the weather radar echo over TPE is red, and flight BR721 will encounter thunderstorm according to the original planned route over TPE. Therefore, the time-dependent displacement parameter equation can be generated by predicting the thunderstorm trajectory, which can be brought into the DWA model of this paper for collision prediction and rerouting planning.

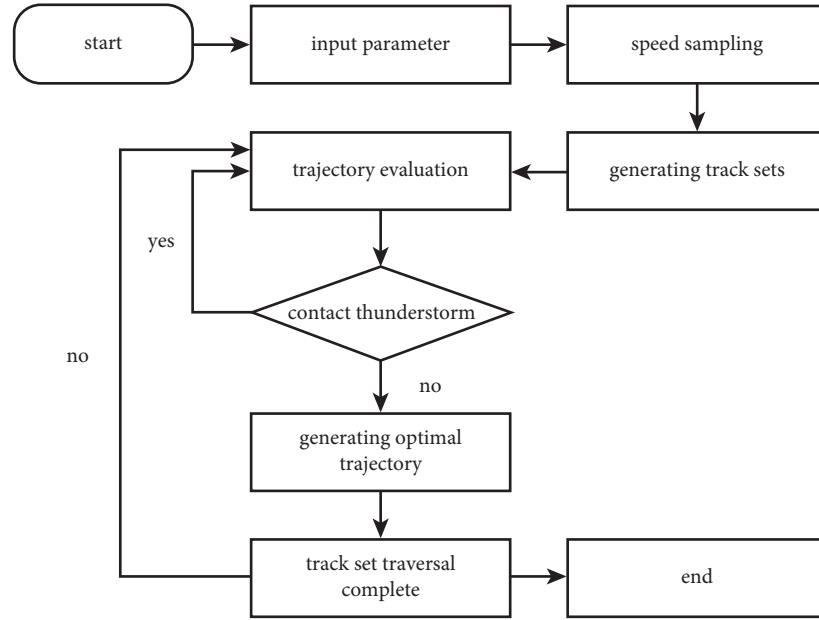


FIGURE 3: Dynamic window algorithm flowchart.

TABLE 2: Initial simulation parameter table.

Aircraft initial position(50 km)	(0, 0)
Initial yaw angle of aircraft (rad)	$\pi/4$
Aircraft initial speed (km/s)	$V = 0$
Target location (50 km)	(9,9)
Maximum speed (km/h)	400
Maximum yaw speed (rad/s)	20.0
Acceleration (km/ss)	0.001
Rotational acceleration (rad/ss)	1
Thunderstorm track (km)	$(y = \cos t + 2.5, x = \sin t + 1)$
Thunderstorm shape (50 km)	$(x, y)(x + 1, y)(x, y + 1)(x + 1, y + 1)$
Minimum distance from thunderstorm cloud (50 km)	0.25

**3.1. Establishing Thunderstorm Displacement Parameter Equation.** Through the observation of weather radar echo map over TPE at different times (as shown in Figure 6), thunderstorms can be found moving to the east over the northwest of TPE. The thunderstorm displacement images displayed by weather radar echo within 210 minutes are superimposed by graphic software, and the thunderstorm displacement trajectory is shown in Figure 7.

To fit the thunderstorm trajectory equation, taking TPE as the starting point, the direction to the east as the  $X$ -axis, and the direction to the north as the  $Y$ -axis, a rectangular coordinate system is established to obtain the thunderstorm displacement model, as shown in Figure 8.

The thunderstorm trajectory can be found as a curve through the model diagram. Therefore, the parameter equation of thunderstorm trajectory can be obtained by polynomial regression fitting. The thunderstorm coordinates at each time are shown in Table 3:

The above data were fitted by polynomial regression [33], and the fitting formula was as follows:

$$\begin{cases} x = a_n t^n + a_{n-1} t^{n-1} + \dots + a_1 t + a_0, \\ y = a_n t^n + a_{n-1} t^{n-1} + \dots + a_1 t + a_0. \end{cases} \quad (11)$$

The fitting results are shown in Figures 9 and 10.

Through the comparison of fitting results, to avoid overfitting, the  $x$  and  $y$  coordinates are fitted by third-order polynomial as the parameter equation of thunderstorm displacement trajectory; the parameter equation is as follows:

$$\begin{cases} x = -0.000005t^3 - 0.0028t^2 + 2.0297t - 154.3332, \\ y = 0.00002t^3 - 0.0082t^2 + 1.0176t + 48.7011. \end{cases} \quad (12)$$

**3.2. Simulation.** The parameters [34], thunderstorm shape, and displacement equation are brought into the model and simulated by MATLAB. The simulation data are shown in Table 4.

The simulated thunderstorm position and aircraft position are shown in Table 5, and the results are shown in Figure 11:

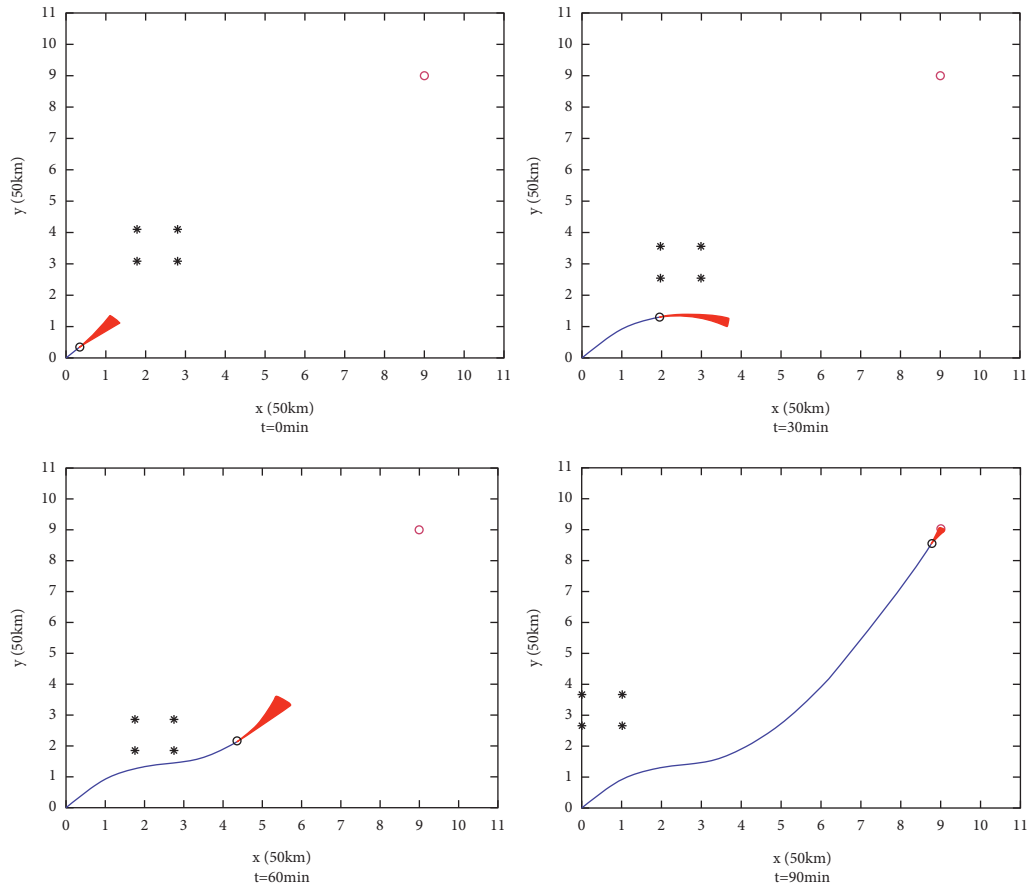


FIGURE 4: Simulation of flight diversion route for aircraft avoiding thunderstorm.

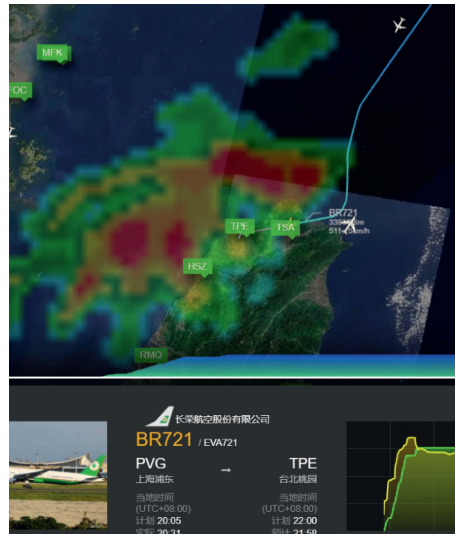


FIGURE 5: Flight chart of BR721.

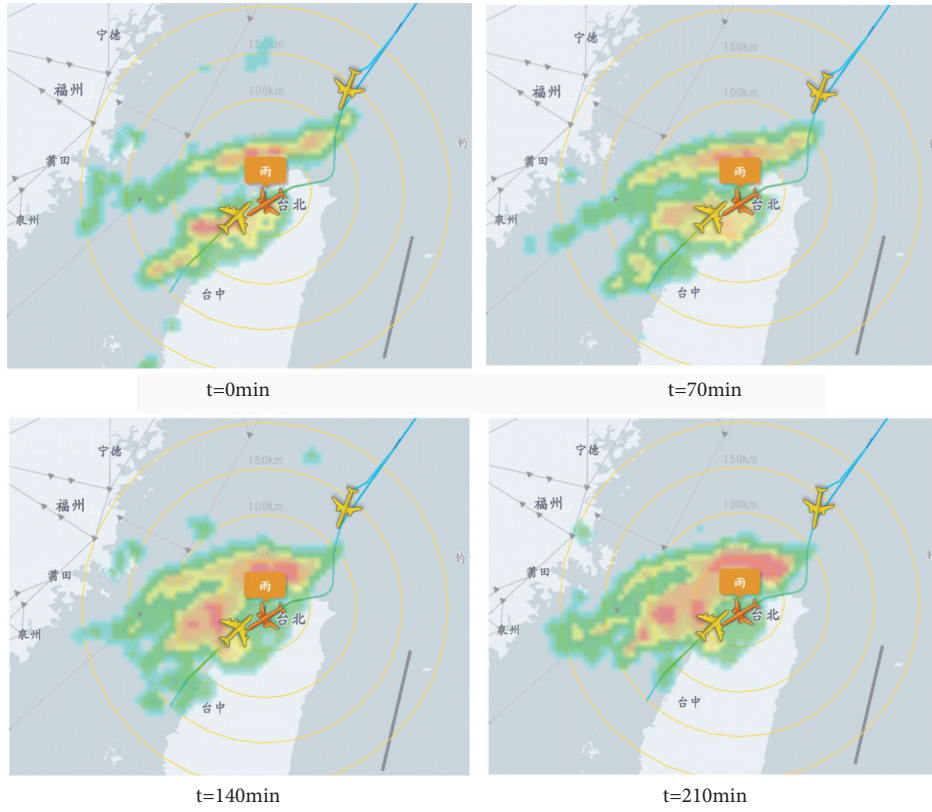


FIGURE 6: Location map of thunderstorm at each time point.

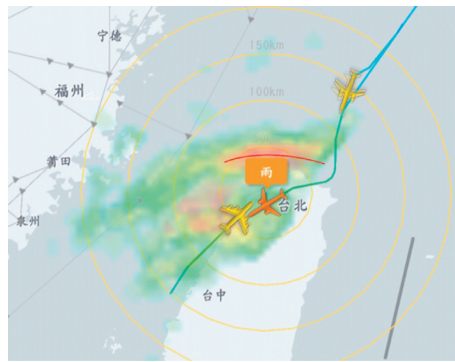


FIGURE 7: Thunderstorm trajectory.

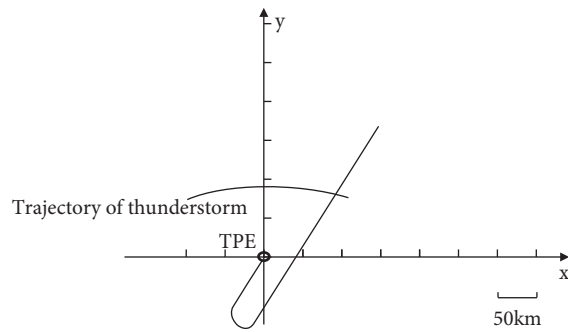


FIGURE 8: Flight movement model diagram.

TABLE 3: Thunderstorm time table.

$t(\text{min})$	35	70	95	130	165	210
$x$ (km)	-86.4	-30.3	10.6	51.2	80.4	102.3
$y$ (km)	75.3	85.4	87.7	83.2	75.2	70.2

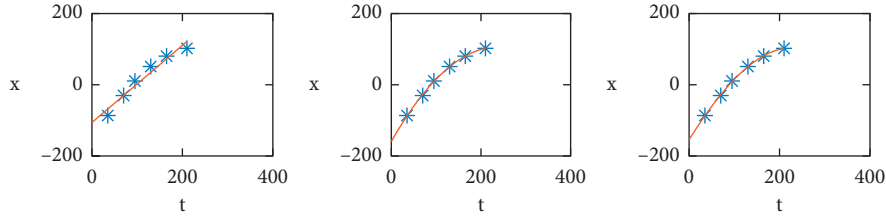


FIGURE 9: Thunderstorm  $x$ -coordinate 1-3 order fitting diagram.

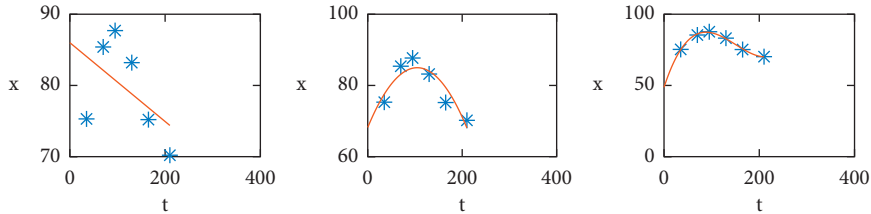


FIGURE 10: Thunderstorm  $y$ -coordinate 1-3 order fitting diagram.

TABLE 4: Case simulation parameters.

Aircraft initial position(km)	(300,300)
Initial yaw angle of aircraft(rad)	$-\pi/4$
Aircraft initial speed (km/h)	800
Starting position of approach (km)	(-10,-30)
Runway entrance location (km)	(0,0)
Maximum speed (km/h)	800
Maximum yaw speed (rad/s)	20.0
Acceleration(km/ss)	0.01
Rotational acceleration(rad/ss)	1
Thunderstorm track (km)	$x = -0.000005t^3 - 0.0028t^2 + 2.0297t - 154.3332y = 0.00002t^3 - 0.0082t^2 + 1.0176t + 48.7011$
Thunderstorm shape (km)	$(x, y), (x - 50, y + 25), (x - 50, y), (x - 100, y)(x, y - 20)$
Minimum distance from thunderstorm cloud(km)	25

TABLE 5: The position of thunderstorm simulation and aircraft parameters.

$t$ (min)	35	70	95	130	165	210
$X_{\text{clo}}$ (km)	-86.4	-30.3	10.6	51.2	80.4	102.3
$Y_{\text{clo}}$ (km)	75.3	85.4	87.7	83.2	75.2	70.2
$X_{\text{air}}$ (km)	290.7	220.3	120.1	100.3	0.4	0
$Y_{\text{air}}$ (km)	292.1	224.1	115.7	12.3	-25.3	0

It can be seen from Figure 11 that the aircraft successfully avoided the moving thunderstorm from the beginning of approach to the end, and its simulated track (blue) is smoother

and more operable and economical than the actual track (red) [35], which provides a new and effective method for approach segment path planning in thunderstorm weather.

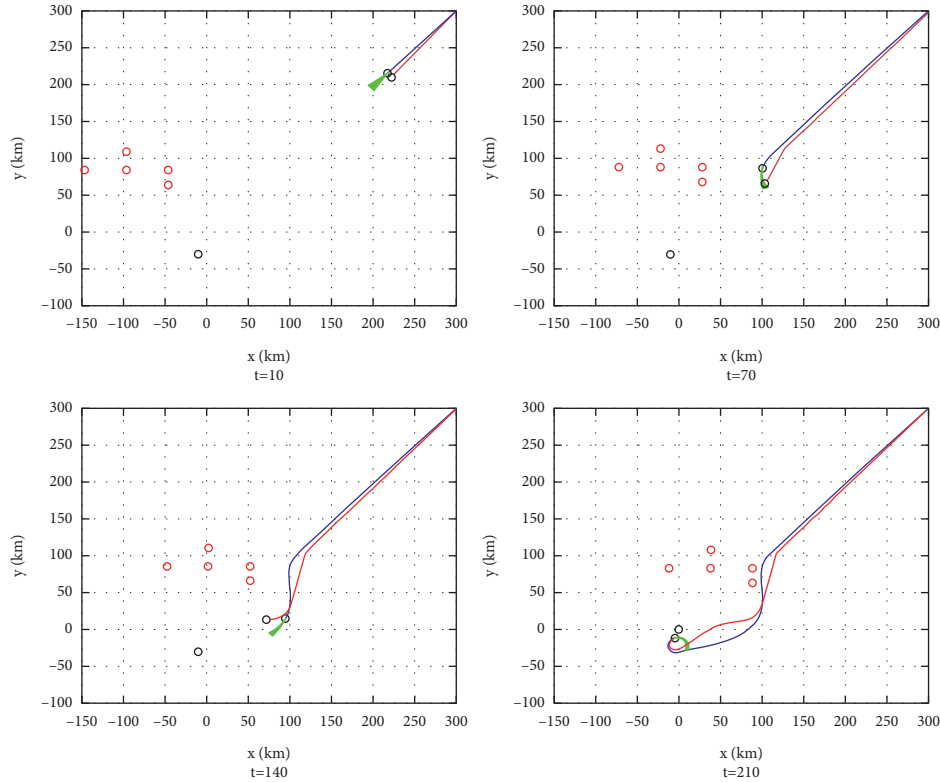


FIGURE 11: Dynamic simulation of flight BR721 avoiding thunderstorm.

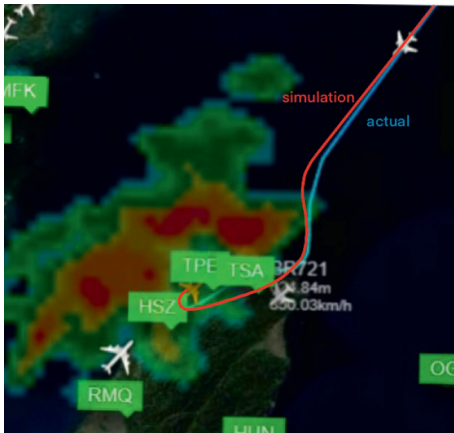


FIGURE 12: Comparison chart of the simulated route and the actual route.

#### 4. Conclusion

In this paper, an improved spatiotemporal dynamic window approach is proposed. The algorithm can deal with the path-planning problem in an dynamic environment by associating the location of obstacles in a single window with time. In SDWA, the traditional DWA algorithm is used for fixed obstacle avoidance along the path, and the location of obstacles in each window is refreshed by time-related location function. Next, move the obstacles under the continuous window along/on with the target trajectory to complete the construction of the dynamic environment. Meanwhile, to

solve the trajectory-planning problem of the approach segment in thunderstorm weather, aiming at the complex shape of thunderstorm, SDWA describes the thunderstorm shape through the setting of obstacle point set, sets relevant motion parameters with reference to the performance of relevant civil aircraft, and sets parameters such as safety distance in combination with relevant requirements for safe flight of civil aircraft. Through the regression analysis of thunderstorm displacement trajectory and time, the thunderstorm displacement trajectory equation is established and applied to constructing a dynamic environment. Finally, SDWA is used to plan the trajectory of the approach segment in thunderstorm weather. The simulated diversion track and the actual diversion track are shown in Figure 12 (blue is the actual motion track and red is the simulation track).

The results show that the SDWA algorithm has good obstacle avoidance performance, which makes reasonable trajectory planning for the aircraft with thunderstorm weather on the route and has highly application to the actual circumstance, and the trajectory is smoother and more economical. Therefore, SDWA provides a safe and efficient method to solve the problem of approach segment path planning under thunderstorm weather. In the future, research should further combine GPS positioning system or Beidou navigation system to improve the implementation accuracy of simulation route [36–38]. Under the new route system, it can further improve the efficiency and safety of diversion planning in thunderstorm weather [39].

However, when SDWA deals with an extremely complicated weather, it may fall into a local loop of the path due



to the problem of parameters' setting, resulting in obtaining the optimal path difficultly. Therefore, the model can be further optimized by combining the optimization algorithm in the future.

## Data Availability

All the data in the study are available.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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