HELICOPTER FORWARD-LOOKING WARNING METHOD BASED ON IMAGE MATCHING FOR URBAN LOW-ALTITUDE FLIGHT

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Abstract
Aiming at the unique geographical characteristics of urban environment, combined with image matching aided navigation and forward-looking warning technology, the helicopter forward-looking warning method based on image matching is studied. Based on precise navigation and positioning, dangerous obstacles are predicted and warnings are generated. Firstly, the image matching algorithm applied to helicopter forward-looking warning is studied, and a normalized cross-correlation matching algorithm based on variable step-size second-order difference fast search strategy is proposed. Then, the principle and algorithm of helicopter forward-looking warning algorithm are given, and the warning boundary is determined based on helicopter escape trajectory. A test example is built to verify the algorithm. The simulation results show that compared with the conventional warning method, the ground proximity warning algorithm based on image matching can effectively correct the navigation error and improve the success rate of the warning, especially suitable for low-altitude anti-collision warning in urban environment. The proposed fast search strategy of variable step-size second-order difference method can effectively improve the speed of the algorithm.

1. INTRODUCTION

As we all know, helicopters have been widely used in urban medical rescue, public security law enforcement, transportation, fire-fighting and other purposes [1-2], because of their good vertical take-off and landing and low altitude flight performance. Compared with other flight environments, the urban flight environment is very complex. When helicopters perform missions at low and ultra-low altitudes, the probability of Controlled Flight Into Terrain (CFIT) is very high [3]. Therefore, it is urgent to apply the Helicopter Ground Proximity Warning System (GPWS) in complex urban environment.

The traditional Ground Proximity Warning System mainly includes excessive drop rate warning, excessive terrain proximity warning, excessive drop after take-off or re-flight warning ,unsafe over-obstacle warning and sliding to excessive departure warning, etc. [4]. Terrain Awareness Warning System (TAWS) developed on GPWS adds forward-looking function based on basic warning mode. The successful use of TAWS in fixed-wing aircraft makes people naturally think of installing TAWS on helicopters, namely Helicopter Terrain Awareness Warning System (HTAWS), to reduce the occurrence of CFIT accidents.

However, the existing helicopter forward-looking warning function is usually only applicable to cruise flight with high flight altitude [5-6]. For helicopters that often need to perform low altitude missions, when the altitude is very low (usually less than 100m), the warning boundary of the warning system is too large, which will produce continuous false warning. Therefore, in order to reduce the false warning of helicopter warning system in low altitude flight, it is necessary to reduce the forward-looking warning boundary on the premise of ensuring flight safety. However, due to the existence of navigation error and terrain database error, the relative position of helicopter and terrain also has some errors. If only the forward-looking warning boundary of helicopter is reduced without any modification, the warning will fail. It can be seen that how to accurately obtain the relative position between helicopter and terrain is the key to helicopter forward-looking warning at low

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altitude.

At present, terrain-aided navigation is mainly used to obtain the precise relative position between helicopter and terrain. Terrain-aided navigation uses radio altimeter and barometric altimeter to determine the location according to the terrain below the fuselage and terrain database, to correct the error of navigation system (such as inertial navigation system) and improve the positioning accuracy. For mountainous, hilly and other environments, it has a good effect, but for urban environment which has high-rise buildings in groups, it is easy to occur drastic changes in terrain elevation and elevation cycle phenomenon terrain-aided navigation in this case is very easy to cause matching failure, so it is not applicable. However, cities have abundant image texture features, and landmark buildings emerge in endlessly. This problem can be solved by image matching method.

Image matching has been a hotspot and difficulty in recent decades, and has been applied in many fields: for example, scene matching is used in cruise missile terminal guidance to determine the accurate position of missile [7]; for unmanned aerial vehicles, image matching is used to locate and identify targets [8]. However, there is no relevant research on the application of image matching technology in helicopter anti-collision warning.

This paper studies helicopter forward-looking warning based on image matching technology. Dangerous obstacles are predicted and warnings are generated based on accurate positioning. Firstly, the image matching algorithm applied to helicopter flight in urban environment is given. Then the principle and algorithm of helicopter forward-looking warning algorithm are given. Finally, a test example is constructed to verify the algorithm and the corresponding conclusions are given.

2. URBAN ENVIRONMENT IMAGE MATCHING METHOD

Image matching can be divided into gray-level matching, feature-based matching and decision-based matching according to the level of image feature extraction. Gray-based image matching algorithm has mature theory, high matching accuracy and good anti-noise performance [9-10]. Therefore, this paper uses the normalized cross-correlation method based on gray-level to match. This method uses a gray-scale array of certain size windows to search and match the pixels of matched image in sequence according to similarity measure. It has the advantages of not affected by scale factor error and strong anti-white noise interference ability [11-12]. The urban surface has rich and unique image texture features, and the range of gray change is larger than that of natural environment. Therefore, this method is very suitable for urban environment image matching.

The helicopter for image matching should have an airborne camera and a satellite image database. Firstly, the helicopter captures the urban environment image in real time, and then compares the captured image with the airborne satellite image data through the normalized cross correlation matching algorithm to determine the best matching position, so as to obtain the precise position of the helicopter.

2.1. Normalized Cross-correlation Matching Method

Normalized cross-correlation matching algorithm judges the matching degree of search graph and template graph by calculating their similarity. The higher the similarity of calculation, the higher the matching degree of search graph and template graph. When this method is applied to image matching of helicopter urban environment, the similarity measure of urban environment images captured by helicopter airborne camera and airborne satellite image database is defined as follows:

(1)

$$R(x,y)=\frac{1}{\mathrm{n}}\cdot\frac{\sum_{x,y}T(x,y)-m_T}{s_T}\cdot\frac{\sum_{x,y}I(x+x',y+y')-m_I(x,y)}{s_I(x,y)}$$

Where x and y are the transverse and vertical coordinates of the template graph separately; n is the total number of pixels of template graph $I(x,y)$; m_T is the average gray level of template graph of satellite map database $T(x,y)$; s_T is the standard deviation of the gray level of the template graph. Namely:

$$\begin{cases} m_T=\frac{1}{n}\sum_{x,y}T(x,y) \\ s_T=\sqrt{\frac{1}{n}\sum_{x,y}[T(x,y)-m_T]^2} \end{cases} \quad (2)$$

Analogously, m_I is the average gray level city of environment image taken by helicopter airborne camera (namely search graph $I(x,y)$); s_I is standard deviation of gray level of the

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photographed image. Here, define x' and y' as the offsets of search graph, then:

$$(3) \quad \begin{cases} m_I = \dfrac{1}{n}\sum_{x,y} I(x+x', y+y') \\ s_I = \sqrt{\dfrac{1}{n}\sum_{x,y}[I(x+x', y+y') - m_I]} \end{cases}$$

The greater the similarity measure $R(x,y)$, the more similar the helicopter's position (x,y) is to the urban environment. x' and y' represent the offset between the search subgraph and the template graph.

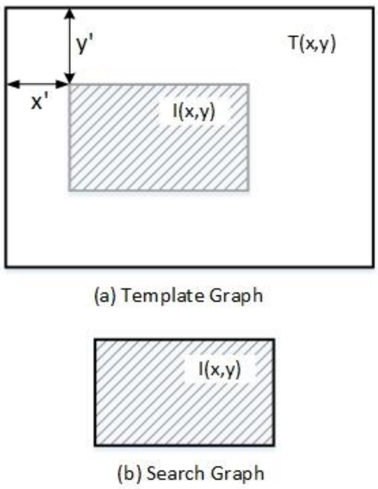

Figure 1 Normalized Cross-correlation Conventional Search Strategy

As shown in Fig. 1, when matching an image, the search starts from the left vertex of the image, from left to right, and from top to bottom. Record the similarity values at each location and form a similarity matrix after traversing the search, as shown in Fig. 2. When the image of urban environment taken by helicopter airborne camera matches the image data of airborne satellite successfully, the current position of helicopter is the maximum of the current similarity.

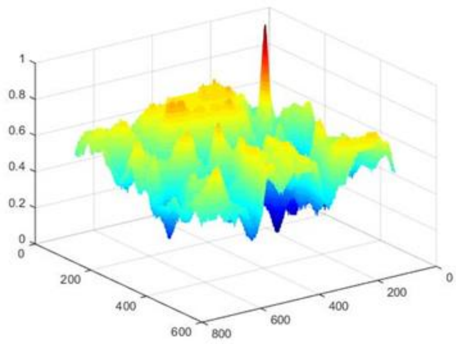

Figure 2 Matching Successful Similarity Matrix

When the calculated maximum similarity is one, it shows that the search graph is identical with the template graph. However, in practice, because of the difference of ambient light, the hardware parameters of the template image and the search image, the gray value of the search image and the template image will be different, so the maximum similarity value is usually between zero and one.

When there is no relevant urban environment image taken by airborne camera in satellite image database, or the image distortion is very serious, the image matching failure will occur. At this time, the similarity matrix is shown in Fig. 3.

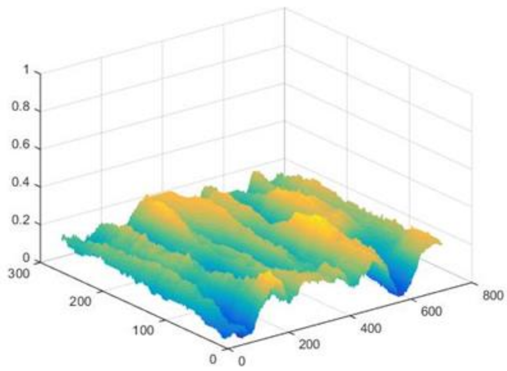

Figure 3 Matching Failure Similarity Matrix

2.2. Fast Image Search Strategy

Section 2.1 shows that the basic principle of the traditional normalized cross-correlation matching method is to move the search image pixels by pixels on the template map, and then compare the similarity values of all locations to determine the matching position. Therefore, this method must traverse all the pixels, and if the amount of template data is very large, the amount of calculation is amazing [11-14]. In order to solve this problem, a variable step size quadratic difference algorithm is

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proposed, which can perform matching more efficiently without affecting the matching accuracy, thus effectively improving the computational efficiency of the algorithm. Specifically as follows:

The Laplacian operator of x and y can be obtained by the second-order difference of one-step for two-dimensional functions.

$$\nabla^2 f(x,y) = \frac{\partial^2 f(x,y)}{\partial x^2} + \frac{\partial^2 f(x,y)}{\partial y^2} \quad (4)$$

The similarity matrix formed by normalized cross-correlation method shows that the difference between two adjacent elements is very small. The second-order difference reflects the change rate of the first-order difference. The faster the value increases, the bigger the second-order difference value is. Laplace operator is a differential operator, which is very sensitive to the sudden change of the value. The larger the value of Laplacian operator in a certain direction, the more violent the change is. Therefore, searching along the direction of increasing Laplacian operator can effectively improve the speed of searching. In addition, this method can effectively avoid the search strategy falling into local optimum, thus improving the probability of finding the best matching position.

From the analysis of normalized coefficient matrix, it can be seen that the normalized correlation coefficients of adjacent pixels at the non-optimal matching position are very close and change slowly, while there is a rapid peak at the optimal matching position. In this case, different search steps for different locations can effectively improve the search efficiency.

The second-order difference of two-dimensional function with step size k can be obtained as follows:

$$\frac{\partial^2 f(x+k,y)}{\partial x^2} + \frac{\partial^2 f(x,y+k)}{\partial y^2} = \frac{\frac{\partial f(x+k,y)}{\partial x} - \frac{\partial f(x,y)}{\partial x}}{k} + \frac{\frac{\partial f(x,y+k)}{\partial y} - \frac{\partial f(x,y)}{\partial y}}{k} \quad (5)$$

The normalized cross correlation coefficients of images with different properties differ greatly when matching. Therefore, the variable step size of second-order difference should be determined according to the characteristics of the image itself. The region with smaller normalized correlation coefficient is suitable for large step size, while near the optimal location, the correlation coefficient is large and varies dramatically, so it is suitable for small step size search. In this paper, the search step k is determined according to three thresholds T_1, T_2 and T_3. The expressions are as follows:

$$\text{K}=\begin{cases} 4, & R < T_1 \\ 3, & T_1 \le R < T_2 \\ 2, & T_2 \le R < T_3 \\ 1, & R \ge T_3 \end{cases} \quad (6)$$

Where R is the normalized correlation coefficient, $\text{T}_2 = \frac{\text{Average gray value}}{\text{Maximum gray value}}$,

$\text{T}_1 = \frac{\text{T}_2}{2}$,

$\text{T}_3 = \frac{1\text{-T}_2}{2} + \text{T}_2$

In this paper, the simulation experiments of traversal, mountain climbing and second-order difference methods are carried out, and the results are shown in Table 1. It can be seen from the table that the speed of the second-order difference method with variable step size is six times faster than that of the ergodic method and more than two times faster than that of the ordinary mountain climbing algorithm.

Table 1 Time comparison of different search strategies

Algorithm	Number	Time/sec	Average Time /sec
Traversing Method	10	61.22	6.12
Hill-Climbing Method	10	27.19	2.72
Variable Step-Size Second-Order Difference Method	10	10.27	1.03

3. HELICOPTER FORWARD-LOOKING WARNING ALGORITHM

The helicopter forward-looking warning algorithm depends on the accurate helicopter position, so combining image matching and forward-looking warning can effectively reduce the probability of inaccurate warning and improve the safety of helicopter flight in urban environment.

3.1. Principle of helicopter forward-looking warning

The working principle of forward-looking warning is based on the flight state of helicopter. A virtual three-dimensional warning boundary is formed in the forward direction space of helicopter. At the

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same time, the data of terrain and obstacles provided by the database are acquired. The spatial position relationship between the warning boundary and the surrounding terrain is compared in real time. When the warning boundary touches the surrounding terrain, it will be Generate an warning [15], as shown in Fig. 4.

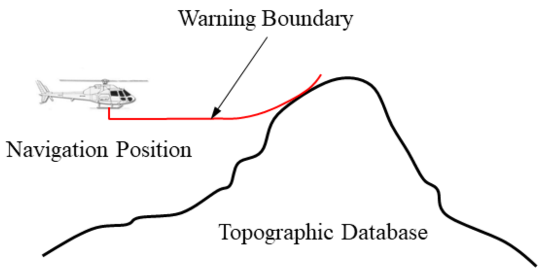

Figure 4 Helicopter forward-looking warning schematic

3.2. Helicopter escape trajectory

According to document [15], the fitting degree between helicopter escape trajectory and parabolic equation is high, and the height H of escape trajectory can be expressed as

$$H = c_0 + c_1 * x_{tr} + c_2 * x_{tr}^{\ 2} \tag{6}$$

Where x_{tr} is the longitudinal coordinate of the trajectory, and c_0 , c_1 and c_2 are the undetermined fitting coefficients. The fitting coefficients are related to the flight performance of helicopters. Usually, they need to be fitted based on flight test data. They can also be obtained by using high-precision helicopter flight dynamics model. The second method is adopted in this paper.

In practical application, for a given aircraft type, the fitting coefficients of escape trajectories under various combined flight states are calculated offline. In actual flight process, the coefficients of escape trajectories under this flight state can be obtained by multi-dimensional interpolation, and the corresponding escape trajectories can be obtained.

3.3. Helicopter Warning Boundary

Reference [16], a 2-sec pilot reaction time is added to the escape trajectory. In addition, due to sensor errors and database errors, the helicopter should have a safe distance under it during flight, that is, the minimum safe height. Therefore, this paper refers to the MXKKII product [18] of Honeywell Company, USA, and sets the minimum safety height to 20m. Taking the demo helicopter as an example, if the initial flight state is: forward flight speed is 10 m/s and descent rate is 4 m/s, the warning boundary is obtained as shown in Fig. 5.

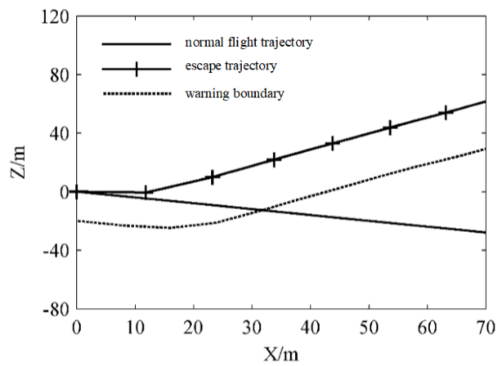

Figure 5 Schematic diagram of escape trajectory and warning boundary of the demo helicopter

4. SIMULATION RESULTS AND ANALYSIS

In order to verify the effectiveness of image matching algorithm in helicopter city pre-flight warning, this paper designs and develops a set of image matching verification program. Firstly, the image matching algorithm is validated, and then the helicopter forward-looking police method based on image matching in complex flight environment is validated.

4.1. Simulation of Image Matching Algorithms

The simulation validation system uses google map data as the airborne map database. The map resolution provided by google satellite map is different in different locations. It has high resolution for big cities, scenic spots and building areas, which can reach 0.5-1m resolution. Therefore, it is very suitable for image matching in helicopter city flight.

The simulation steps are as follows:

Firstly, the template map is set up. As shown in Fig. 6, a rectangular urban area in google satellite map is selected, which ranges from 118.757855E to 118.81339874E (longitude), 56.15344048N to 56.14991069N (latitude), and its area is about 200 924.66 m^2.

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Figure 6 Template Diagram Settings

In this paper, the aerial photograph of a multi-rotor aircraft at 50 m altitude is used as the detection image of an airborne camera, as shown in Fig. 7 (a). The proportional relationship between aerial photograph and satellite image is determined by the geometric relationship between image scale and flight altitude. Then, the aerial photograph is transformed to the same scale as satellite image through the Gauss pyramid method. The transformed image is shown in Fig. 7 (b). Using the normalized cross correlation coefficient matching method for image matching, its similarity surface is shown in Fig. 8. By traversing the similarity values of each location, the position with the greatest similarity is selected as the best matching position. Taking the left vertex of the image as the origin of coordinates, the right direction as the x-axis positive direction, and the downward direction as the y-axis positive direction, the optimal matching position in the current satellite image is coordinates (446, 302), and the red box in Fig. 9 is the algorithm matching position.

(a) Original aerial photograph

(b) Transformed aerial photograph

Figure 7 Search Graph

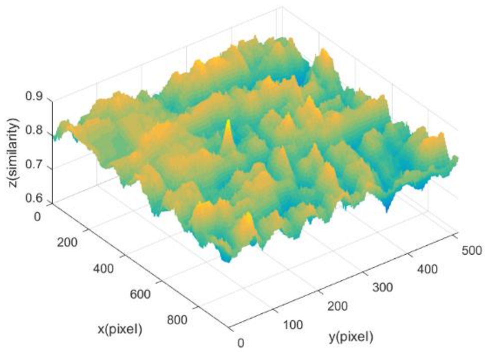

Figure 8 Similarity Surface

Figure 9 Matching Results Settings

Thus, the image matching algorithm in this paper can effectively realize the matching between the actual image and satellite image, so as to

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determine the exact location of helicopter City Flying at low altitude.

4.2. Warning algorithm simulation based on image matching

In order to verify the correctness of the method of helicopter City pre-flight warning based on image matching proposed in this paper, a simulation is carried out to verify it. In the simulation, two test groups are set up. The first group uses image matching method to test, and the other group is the control group using conventional warning algorithm. The two test groups have the same warning boundary. Both test groups use the warning boundary based on escape trajectory, and the minimum safe height is 15 m. However, the control group does not combine image matching algorithm. It can correct the navigation error of helicopter in urban environment.

Firstly, helicopter flight parameters are set up: simulation is based on certain helicopter flight dynamics model. The helicopter departs from position A in Fig. 10. The altitude of the helicopter is 11m, the initial roll angle is 0 degrees, the pitch angle is 0 degrees, and the heading angle is 0 degrees. At the altitude of 55m, the helicopter flies horizontally at the speed of 10 m/s. The average radio altitude is about 43 m, and the end is position B. The simulation test will be stopped if an warning occurs during the flight or the end point is reached.

Then the error parameters are set: at the beginning of the test, both groups have 30 m lateral navigation, and the error direction is the right side of the helicopter flight direction.

The satellite maps of the area shown in Fig. 8 are combined with the digital elevation maps generated by building height. The three-dimensional maps of the digital elevation maps are shown in Fig. 11, which can be seen from the maps, two buildings near this route, one of which is about 48.5 m in height and 82 m in width, and the other is about 22 m in height and 77 m in width. There is no risk of collision.

In the simulation test, the control group used the conventional warning algorithm to generate the warning boundary based on the navigation position, while the experimental group used the image matching algorithm. The actual position and the warning boundary were all based on the matched position. Fig. 12 is the track diagrams of two test groups under the same terrain in the test. The experimental group successfully warned, while the control group failed to warn, resulting in the helicopter crashing into the building.

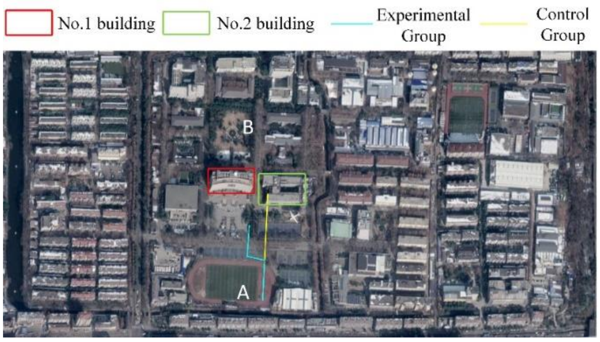

Figure 10 Track maps of experimental group and control group

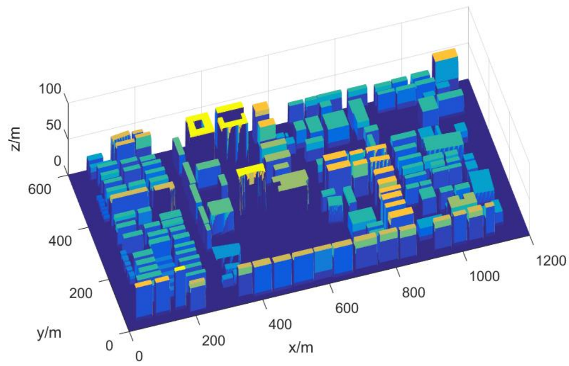

Figure 11 Digital Elevation Map

The experimental group matched the images every 2 seconds to correct the navigation errors. The warning boundary intersected with the building No. 1 under the real route, and the warning occurred, a s shown in Fig. 12 (a). However, the navigation position of the control group is on the right side of the actual position, and the dangerous building can not be detected, so no warning occurs, as shown in Fig. 12 (b), while the real flight path intersects with the building and collision accident occurs.

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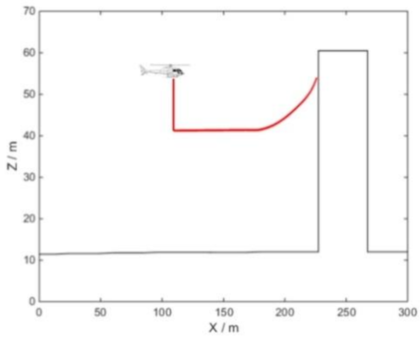
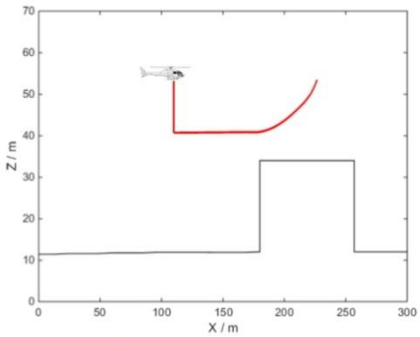


(a) Successful warning in experimental group



(b) Failed warning in comparison group

Figure 12 Comparison of warning results between experimental group and control group

Fig. 13 shows the time-varying curve of relative position errors between helicopters and buildings of two test groups in urban environment. It can be seen from the figure that the relative position errors of both groups are 30 m at the beginning of the simulation, but the navigation errors of the experimental group are corrected by image matching.

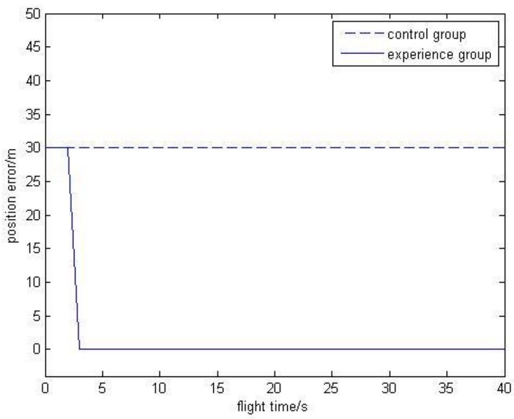


Figure 13 Relative error comparison

In summary, the positioning error of helicopter can be corrected effectively by combining image matching method and forward-looking warning algorithm, which can effectively improve the success rate of flight warning in urban environment.

5. CONCLUSION

In this paper, the image matching method based on normalized cross correlation is applied to helicopter urban forward-looking warning, which effectively corrects the error of navigation system. The helicopter forward-looking warning police method based on image matching is studied, and the helicopter urban flight anti-collision warning is effectively realized based on accurate navigation and positioning. The main conclusions of this paper are as follows:

1) Combining with the image matching helicopter forward-looking warning algorithm, the navigation error is effectively corrected, and the success rate of the warning is improved. It is proved that the proposed image matching based helicopter urban forward-looking warning police method can well meet the requirements of helicopter anti-collision warning in low altitude flight in urban environment.

2) Based on normalized cross-correlation, image matching uses ergodic method to calculate the similarity matrix between two images, which requires a large amount of computation. In this paper, we use variable step-size second-order difference method to image matching more efficiently, which effectively improves the speed of image matching.

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