Optical navigation of unmanned aircraft systems

A Prisyazhnyuk, A Karmanov, S Prisyazhnyuk, N Karmanova, A Makarenko
Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics, 49 Kronverksky Avenue, Saint Petersburg 197101, Russian Federation

*Corresponding email: karmanov.nip@gmail.com

Abstract. Improving machine vision in robotic systems for large-scale sensing in forestry is more relevant than ever. Currently, most UAVs are equipped with various navigation systems (SN), including optical ones. Automatic return-to-point systems are also widely used. These systems are used to facilitate piloting by aircraft, or activated in case of emergency situations. There are also optical tracking systems for the object, which are used mainly in video shooting. Optical navigation systems can be used to more accurately position spaces, and can also be used as a backup navigation system when the main navigation system fails.

1. Introduction

1.1. Theoretical calculations
Improving machine vision in robotic systems for large-scale sensing in forestry is more relevant than ever. The best sign for determining the angle of an image is the spatial two-dimensional spectrum. To get the spectrum, you need to use the Fourier transformation. For a discrete two-dimensional case, Fourier's transformation is expressed by the following equality:

\[ F(u, v) = \frac{1}{M \times N} \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x, y) \exp \left[ -i2\pi \left( \frac{ux}{M} + \frac{vy}{N} \right) \right] \]  

(1)

where, \( f(x, y) \) is a function of two variables with sizes \( M \times N \), \( x = 0, 1, 2, ..., M - 1 \), \( y = 0, 1, 2, ..., N - 1 \). This expression should be calculated for all \( u \) and \( v \). The variables \( x \) and \( y \) are called spatial variables or image variables. Variables \( u \) and \( v \) - transformation variables or frequency variables.

In order for the origin of the Fourier transform to be in the center of the \( M \times N \) rectangle, the original image \( f(x, y) \) is multiplied by \((-1)^{x+y}\). By such an action, it can be achieved that the origin of coordinates of the image \( F(u,v) \) shifts to a point with frequency coordinates \((M/2, N/2)\). When working with images, the frequencies that make up the spectrum are usually called spatial frequencies. Spatial Frequency -the number of brightness repetition periods per unit length. The spatial spectrum allows you to highlight the presence of vertical and horizontal lines in the image. As can be seen from figure 1, the slope of the lines that show the main frequencies of the images corresponds to the slope lines in the original image [1]. Thus, finding the direction of the most powerful component of the spectrum, we can calculate the angle of rotation of the image.
In order to obtain clearer spectra for this task, additional image training can be made.

2. Methods and Materials

2.1. Correlation analysis
Correlation analysis is used to determine the degree of communication between the two signals. The correlation of the two signals is the correlation factor [2].

In general, the correlation of the standard \(w(x, y)\) with dimensions \(m \times n\) with the image \(f(x, y)\) with dimensions \(M \times N\) is given by

\[
c(x, y) = \sum_{s} \sum_{t} w(s, t) f(x+s, y+t),
\]

where summation is done on the intersection \(w\) and \(f\). This expression is calculated for all sorts of \(x\) and \(y\) variables, so that each \(w\) element at some point falls on each pixel \(f\), assuming that the image sizes are larger than the size of the reference. Spatial correlation is associated with Fourier's transformation according to the correlation theorem

\[
\text{COR}(f, w) \leftrightarrow F^\ast(u, v)W(u, v),
\]

where, \(F\) and \(W\) Fourier-images functions \(f\) and \(w\) respectively, and the symbol means a complex pairing. But it should be noted that when calculating spatial correlation with this condition, it is necessary that the functions \(f\) and \(w\) were the same size. The correlation ratio is expressed by the following equality:
$$\gamma(x, y) = \frac{\sum_x \sum_t [w(s,t) - \bar{w}] [f(x+s,y+t) - \bar{f}_{xy}]}{[\sum_x \sum_t [w(s,t) - \bar{w}]^2 \sum_x \sum_t [f(x+s,y+t) - \bar{f}_{xy}]]^{1/2}}$$

(4)

where the summation is over all pairs of coordinates common to $f$ and $\bar{f}$ average [3].

The value of the mask items $w$ (calculated only once) and $\bar{f}$ Average value of the elements of the image $f$ in the area that coincides with the current position $w$. The $w$ mask is often referred to as a reference, and the correlation calculation is called a reference. The correlation factor $\gamma(x, y)$ varies from -1 to 1. The maximum value $(x, y)$ is achieved when the normalized (by subtracting the average value) standard and the corresponding region in $f$ (also normalized) have the greatest similarity. A minimum is achieved when both normalized functions have the least similarity [4].

Figure 2. Correlation-to-reference scheme.

Figure 2 shows the $w$ standard with dimensions $m \times n$ centered at an arbitrary point $(x, y)$ of the image $f$. At this point, using the formula (4), the correlation coefficient is calculated, the next step, the standard is shifted to a neighboring point, and the procedure is repeated. The complete set of correlation coefficients $\gamma(x, y)$ is found by enumerating the values of $x$ and $y$ so that the center of the standard $w$ passes through all the values of $f$. After that, the maximum value $\gamma(x, y)$ is found, the coordinates of the found point $(x, y)$ are the coordinates of the maximum coincidence of the image $f$ with the standard $w$ [5].

The algorithm described above requires a lot of calculations. Typically, algorithms are used to simplify computations using Fourier’s rapid conversion, as this action allows you to replace multiplication operations with addition operations. The correlation factor can also be calculated using the following equality:

$$\gamma(x, y) = \frac{\text{COR}(f,w)}{\text{COR}(f,q)}$$

(5)

where, the COR operator is the calculation of the correlation according to formula (2), $x$ is the image with dimensions $x \times y$, $w$ is the standard with dimensions $m \times n$, $q$ is the image with dimensions $m \times n$ filled with units (thus limiting the area in which the correlation is calculated). Using the correlation theorem (3), expression (5) takes the following form:
\[ \gamma(x, y) = \frac{\text{IFFT}[F(u, v)W^*(u, v)]}{\text{IFFT}[F(u, v)Q^*(u, v)]} \]  

where, IFFT is the reverbetable operator of Fourier, \( F \), \( W \), and \( w \)-images of \( f \), \( w \) and \( q \) functions respectively, is a symbol of complex pairing. Expression:

\[ \gamma(x, y) = \frac{\gamma(x, y)}{\gamma_{\text{max}}} \]  

where, \( \gamma_{\text{max}} \) is the maximum value of the function \( \gamma(x, y) \). This expression is calculated for all pairs of coordinates \((x, y)\). Thus, the correlation coefficient will vary in the range from 0 to 1, where 1 is the complete coincidence of the standard \( w \) with the image \( f \). The coordinates of the point \( \gamma(x, y) = \gamma_{\text{max}} \) correspond to the coordinates of the point \((x, y)\) of the image \( f \) at which it coincides with the standard \( w \) as much as possible. When using equality (6), there is no need to calculate the correlation coefficient at each image point \( f \), because calculation is done in parallel. Figure 3 illustrates an example of calculating the correlation coefficients using expression (6).

![Figure 3](image_url)

Figure 3. Illustration of the search for the standard in the image. (a) - image, (b) - benchmark, (c) - graph of correlation ratios \( q(x, y) \).

Figure 3 (c) shows that the coordinates of the maximum correlation coefficient correspond to the coordinates of the position of the standard in the image.

This way you can search for objects in the image, as well as compare images with each other.

2.1.1. Algorithm. Using the above dependencies, you can build an algorithm to solve the problem of automatic flight of UAVs over railway tracks, roads or pipelines. The two main parts of this algorithm are:

1) Calculate the angle of the object on the underlying surface. Roads or railways are the targets for this task.

2) Finding a place to land a UAV. The aircraft must automatically identify the area in which it is necessary to land. Using this algorithm to automatically return to the starting point, the place where
the UAV will land is the place of its takeoff.

2.1.2. *Finding the angle of the object's turn.* The Fourier-spectrum image property was used to find the angle of the object located on the observable underlying surface [6]. This process can be divided into three steps:

1) Calculating the spatial spectrum of the image (figure 4);

2) Finding the sum of the amplitude of all the harmonics of the spatial spectrum in directions corresponding to the angles of the turn in the range from 0 to 180 degrees. Since the spectrum is symmetrical relative to the center, calculations can only be done on half of the spectrum image (figure 5).

Knowing which tilt angle corresponds to the direction with the maximum sum of harmonics, we can judge the angle of rotation of the object. The calculated angle of the original rectangle is 30 degrees, which corresponds to reality [7].

The algorithm’s resistance to noise in the image was also tested. To do this, Gaussian white noise with different parameters of D variance and mathematical expectation M was added to the original image.

Figure 6 illustrates the result of an algorithm to find an object angle with Gausses white noise in the original image with the parameters of the variance D - 0.065 and mathematical expectation.
Based on the results, we can conclude that this algorithm is quite resistant to noise [8].

To illustrate the work of this algorithm in the conditions of the task to solve, a schematic image of the road was used (figure 7). No more than 30%. That is, when the window is 512 to 512 pixels, the offset step should be less than 153 pixels.

From the presented data, we can conclude that this algorithm allows you to move the area of interest along the curve line [9].

2.2. Finding a place to land a UAV
To find the landing site, it is necessary to carry out a correlation-extreme analysis of the sequence of images. The algorithm includes the following steps:

1) Calculate the correlation value by the formula (6) by finding the maximum value of the resulting function $\gamma_{max}$. In this case, the standard $w(x, y)$ and image $f(x, y)$ will be the same frame, i.e. This action calculates the autocorrelation. The resulting value is taken as a complete match (100%).

2) Comparison of the sequence of frames with the standard. At each step of shifting the region of interest, the resulting frame is compared with the reference using equality (6). In this case, $f(x, y)$ is the current frame, and $w(x, y)$ is the standard. After that, the maximum value of the correlation function at the moment $\gamma_n$ is calculated. If the current value of the correlation $\gamma_n$ is less than 96% of $\gamma_{max}$, then the region of interest is shifted to the next point according to the selected step.

3) Stop at the start point. If the inequality $\gamma_n > \gamma_{max} \times 0.96$ is satisfied, the motion should be stopped. For more accurate positioning, it is also necessary to fulfill the inequality, $\gamma_n - 1$, where $\gamma_n - 1$ is the correlation value for the position of the frame in the previous coordinates. The steps above allow you to determine the coordinates of the start point.

A generalizing of the two algorithms described above can be compiled an algorithm for the work
of the correlation-extreme UAV stabilization system (figure 8).

1) Get a current image of the underlying surface;
2) Calculate the angle of the angle of the object that is in the resulting image;
3) Calculating the correlation ratio between the current and the reference image;
4) Comparing the current correlation ratio with the threshold;
5) If the current correlation ratio is higher than the threshold, you need to stay at the current coordinates. Otherwise, continue the movement and repeat the steps 1-5.

Figure 8. Algorithm block scheme.

3. Conclusions
In the course of the work, the signs were formulated, the analysis of which allows to solve the problems. The sign that characterizes the angle of the object is the two-dimensional spatial spectrum. By the position of the amplitude of the harmonics of the spectrum, it is possible to determine the angle of the object. The method that analyzes this trait is to compare the amount of amplitude of spatial spectrum harmonics calculated in different directions.

An algorithm has also been developed that allows you to determine coordinates and adjust the course of UAVs when driving over roads, railway tracks and pipelines. To use this algorithm in the UAV’s automatic stabilization system, only a TV camera and a computational device are needed to process the signal coming from the camera.

References
1. Zinchenko O 2011 Unmanned aerial vehicles: the aerial photography for mapping R. 1 1-12
2. Glagolev V and Ladonkin A 2016 Optical navigation system for aircraft I TulSU 10 186-93
3. Baklitsky V 2009 Correlation-extreme methods of navigation and guidance N. SFU 1 360
4. Baklitsky V and Yuryev A 1982 Correlation-extreme navigation methods Radio and Com. 9
5. Syryamkin V and Shidlovsky V. 2010 Correlation-extreme radio navigation systems *Tom. U.* 4 316
6. Vinokurov L 2017 Device for receiving and processing an optical test signal of an unmanned aerial vehicle landing system: *WRC* 2 52
7. Gonzalez R and Woods R 2012 Digital Image Processing *SASGIS* 1104
8. Blagodaryaschev I, Antoxin E, Fedulin A and Panichev V 2019 Application experience of military operation simulation based on virtual reality techniques for military robotic systems evaluation *Rob. and Tech. Cybernetics* 7 94-9
9. Fedulin A and Dmitriev A 2014 The choice of the optimal plan for the use of the forest land reclamation machinesystem *B. of KrasSAU* 9 164-70