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# ERROR MODEL OF HEADING CHANNEL IN VISION-BASED CORRELATION-EXTREME NAVIGATION

*Heading determination algorithm is proposed based on the correlation on pair of geo-referenced image and current one. Correlation is done between the descriptors of feature points determined by Speed-Up Robust Feature (SURF) method. Error metric of matched pair is selected as normalized correlation coefficient (NCC) from the point of view of computational efficiency. The errors of heading determination are investigated for different threshold values of NCC and then the incremental approach is proposed. The constant and random components of heading errors are extracted and on the base of normal distribution the model of errors of heading channel in vision-based navigation is designed.*

***Keywords***: *correlation-extreme navigation, Speed-Up Robust Feature, normalized correlation coefficient.*

## Introduction

The low-cost unmanned aerial vehicle (UAV) integrates Global Positioning System (GPS) and Inertial Measurement Unit (IMU) and usually has ability to perform autonomous flight and automatic navigation along planned waypoints. If the GPS signal for some reason becomes unavailable or corrupted, the state estimation solution provided by data from IMU alone drifts in time and will be unusable after a few . The GPS signal also becomes unreliable when operating close to obstacles due to multi-path reflections. In addition, it is quite vulnerable to jamming (especially for a GPS operating on civilian frequencies). Vision-based navigation is one of possible alternative solution in this case. A camera is usual sensor which can be used to solve navigation related problems. Almost every UAV already has a video camera as a standard sensor in its payload package. Heading determination is possible from a vision-based correlation-extreme navigation, which may be additional source of data fusion in the integrated navigation complex.

Basic techniques for UAV attitude determination by vision-based navigation are considered in [1]. Most of them require the visibility of horizon line to estimate the roll and pitch and therefore are limited in use, especially in urban areas for low level flight. Approaches based on feature alignment use the feature points found on the pair of images to find the transformation matrix (homography matrix).

## Problem statement

Most of the recent work [2] on visual odometry for airborne applications is based on homography estimation under a planar scene assumption. In this case the relation between points of two images can be expressed as $\mathbf{x} \approx \mathbf{H}\mathbf{x}'$, where $\mathbf{x}'$ and $\mathbf{x}$ are the corresponding points of two images expressed in homogeneous coordinates, and $\mathbf{H}$ is the 3×3 homography matrix. The symbol $\approx$ indicates that the relation is valid up to a scale factor. A point is expressed in homogeneous coordinates when it is represented by equivalence classes of coordinate triples (kx, ky, k), where k is a multiplicative factor. The camera rotation and displacement between two camera positions, $c_1$ and $c_2$, can be computed from the homography matrix decomposition [2]:

$$\mathbf{H} = \mathbf{K}\left(\mathbf{R}_{c1}^{c2} + \frac{1}{d}\mathbf{t}^{c2}\mathbf{n}^{c1T}\right)\mathbf{K}^{-1}, \qquad (1)$$

where $\mathbf{K}$ is the camera calibration matrix determined with a camera calibration procedure, $\mathbf{t}^{c2}$ is the camera translation vector expressed in camera 2 reference system, $\mathbf{R}_{c1}^{c2}$ is the rotation from camera 1 to camera 2, $\mathbf{n}^{c1T}$ is the unit normal vector to the plane being observed and expressed in camera 1 reference system, and *d* is the distance of the principal point of camera 1 to the plane.

The goal then is to compute the UAV orientation in horizontal plane, that is heading $\psi$, in the navigation reference system from (1). The coordinate transformation between the camera and UAV is realized with a sequence of rotations. The translation between the two frames will be neglected since the linear distance between them is small.

Coordinates of points on the pair of images are determined using SURF detector [3]. In general case the descriptor of feature point by SURF method includes the following information: coordinates $P=\{x,y\}$, scale of Gaussian filter $M=\{\sigma\}$, gradient orientation $R=\{\varphi\}$, Laplacian $L=\{0,1\}$ (means either white spot on black background or black spot on white), and gradients of quadrants $D=\{D_1,D_2,...,D_{64(128)}\}$, which surround the point. SURF detector is invariant to scale, displacement and rotation but is not invariant to affine distortions. Therefore, here and after it is supposed that heading is determined in strictly horizontal flight and camera is looking downward and is rigidly fixed to UAV.

## Algorithm of heading determination

The coordinates of feature point on the base (geo-referenced) image and on the current image are designated as $\begin{bmatrix} x \\ y \end{bmatrix}$ and $\begin{bmatrix} x' \\ y' \end{bmatrix}$. To simplify calculation that must be realized in real time, the expression (1) is used with camera intrinsic matrix as following $\mathbf{K}=\begin{bmatrix} 1 & 0 & L_x/2 \\ 0 & 1 & L_y/2 \\ 0 & 0 & 1 \end{bmatrix}$, where $L_x$, $L_y$ are dimension of images. Coordinate system of image $Ox_1y_1$ used in most application software is represented as it is shown in Fig.1, where $y$-axis is directed downwards. Coordinate system of camera $Ox_2y_2$ is obtained by conversion using the camera intrinsic matrix **K** and will be used further as main one to determine the object heading $\psi$.

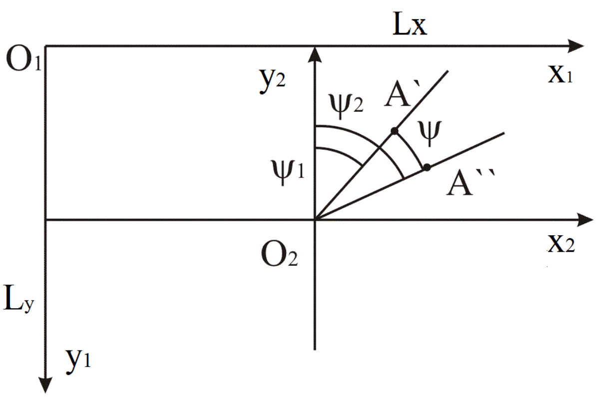


Fig. 1. Coordinate systems of image and camera

As it can be seen from Fig. 1, the heading of point A' (designated as $\psi_1$) can be determined as $\psi_1=\text{atan2}\frac{x_{A'}}{y_{A'}}$ where the function atan2 is the function of arc tangent in the range $(-\pi,+\pi)$. After the rotation of camera around its optical axis the new position of point A" will determine the heading as $\psi_2=\text{atan2}\frac{x_{A''}}{y_{A''}}$. The angle of camera rotation $\psi$ will be a difference between these two angles:

$$\psi=\psi_2-\psi_1. \tag{2}$$

Using SURF method on the pair of images results in obtaining the feature point descriptors on the reference image $\{(x_1,y_1),(x_2,y_2),...,(x_N,y_N)\}$ and on the current one $\{(x'_1,y'_1),(x'_2,y'_2),...,(x'_M,y'_M)\}$, where total numbers of detected feature points on the images are designated as N and M, respectively. The resulting feature points must be matched via correlation using definite error metrics. Extremes of error metrics must be found and localization of matched pairs will be done.

Three main error metrics are usually used to match the points: sum of absolute differences (SAD)

$$\mathbf{E}_{SAD}=\sum\left|\mathbf{D}_i-\mathbf{D}_j\right|,$$

sum of squared differences (SSD)

$$\mathbf{E}_{SSD}=\sum\left(\mathbf{D}_i-\mathbf{D}_j\right)^T\cdot\left(\mathbf{D}_i-\mathbf{D}_j\right),$$

and normalized cross-correlation (NCC)

$$\mathbf{E}_{NCC}=\sum\mathbf{D}^T{}_i\cdot\mathbf{D}_j, \tag{3}$$

where $\mathbf{D}_i$, $\mathbf{D}_j$ - matrices of detected feature points i and j on the pair of images. It is obvious that in all of the cases the error metric will be the matrix of dimension N-by-M.

For the research the NCC error metrics (3) has been selected since it can be calculated by pure descriptor matrices multiplication and therefore realized in real time. The false matching is eliminated by setting the definite threshold value for NCC metric.

Each reliable pair of matching is then used to calculate the heading by (2). The obtained values are then weighted (based on a priori expectation if available) and averaged.

## Experimental results

The study of proposed algorithm has been done on the series of images of camera from the same position with rotation around optical axis by step in 46° (Fig. 2).

Matching has been done between the reference image assumed to be taken with zero heading and current one. Realization of SURF method in (Code of SURF listing in MATLAB) has been used in practice for experiments. Tests have been done in MATLAB 7.8.0. Threshold value has been used in the range from 0,985 to 0,995. The errors of heading determination are shown in Fig. 3, Fig. 4 and Fig. 5.

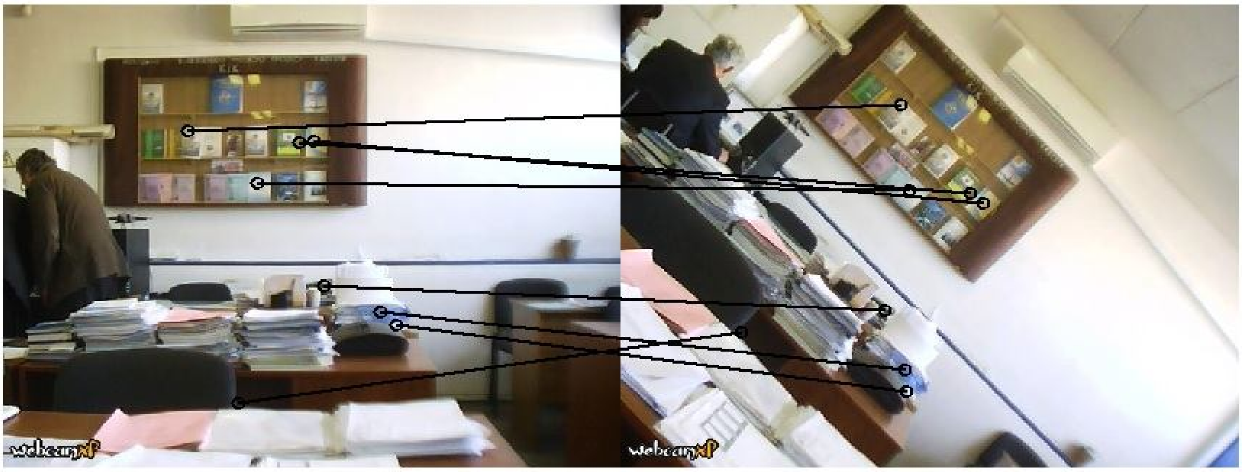

Fig. 2. Referenced image (left) and the same scene with camera rotation angle in 46°.
Matched points are shown by line connections

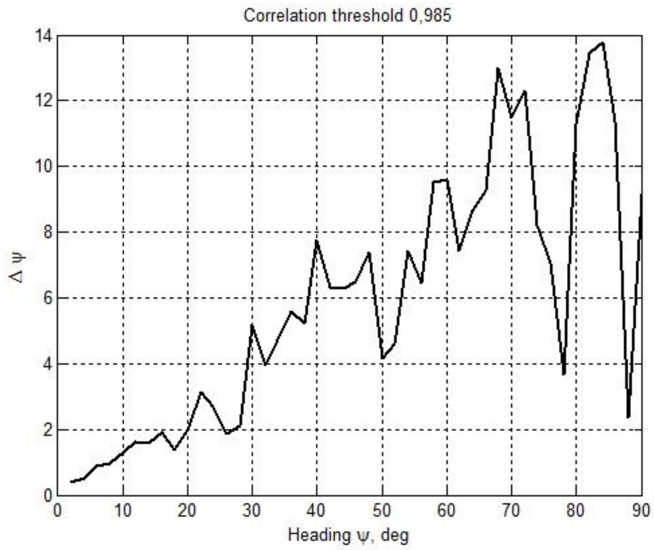


Fig. 3. Error of heading by correlation threshold 0,985

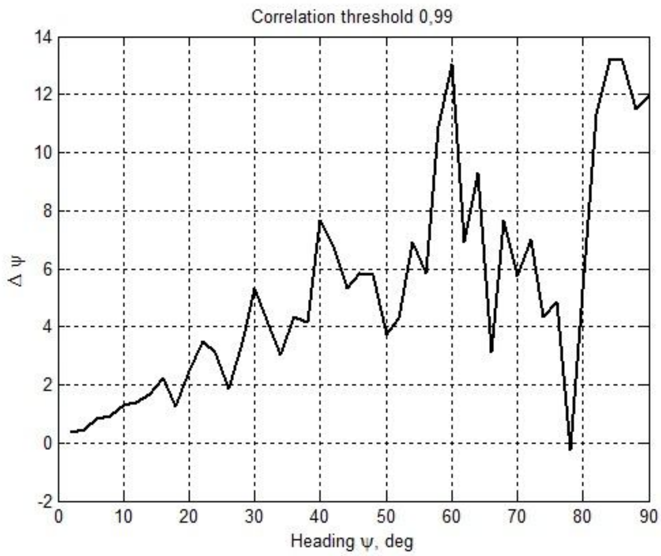


Fig. 4. Error of heading by correlation threshold 0,99

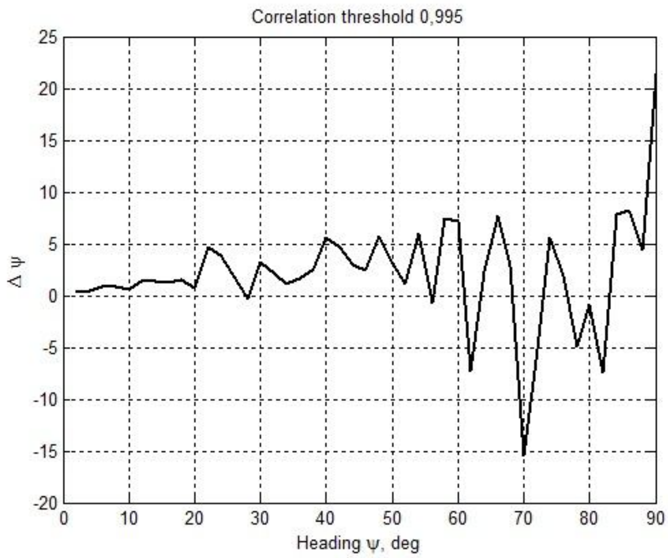


Fig. 5. Error of heading by correlation threshold 0,995

Errors of heading determination of the proposed algorithm are significantly increasing with degree change between reference and current images. The measure of reliability of obtained data can be in the form of variance of heading measurement for matched points (Fig. 6, Fig. 7, Fig. 8).

Smaller errors have been observed for incremental heading determination (Fig. 9) when heading is determined by the difference of two images between two sequential moments of rotation in the assumption that heading for the first image is known.

As it can be seen the constant component in heading error is present and can be determined. For the given experiments it has been 0,1768°. Eliminating the constant component it is possible to obtain the random component of error (Fig. 10).

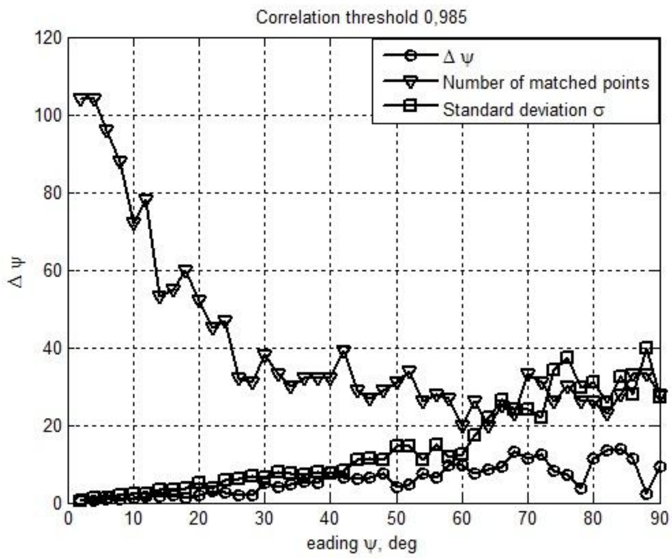


Fig. 6. Dependence of the heading error on the variance and number of matched points with correlation threshold 0,985

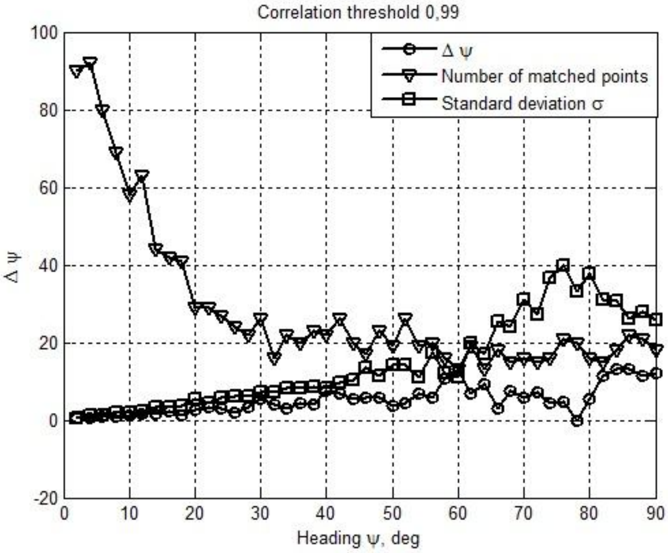


Fig. 7. Dependence of the heading error on the variance and number of matched points with correlation threshold 0,99

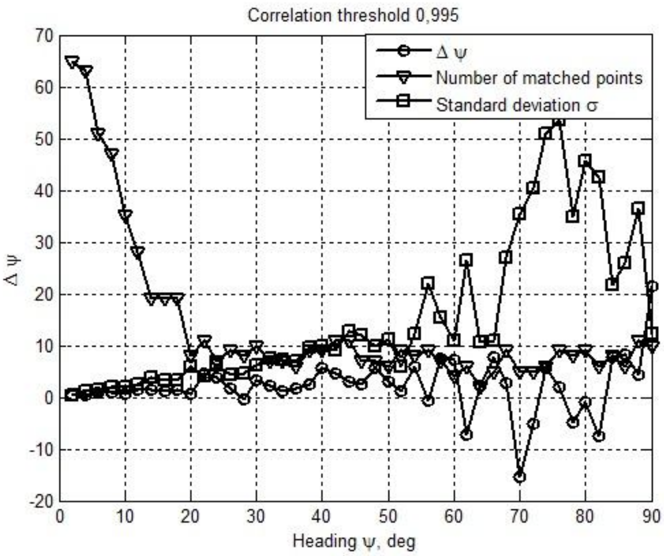


Fig. 8. Dependence of the heading error on the variance and number of matched points with correlation threshold 0,995

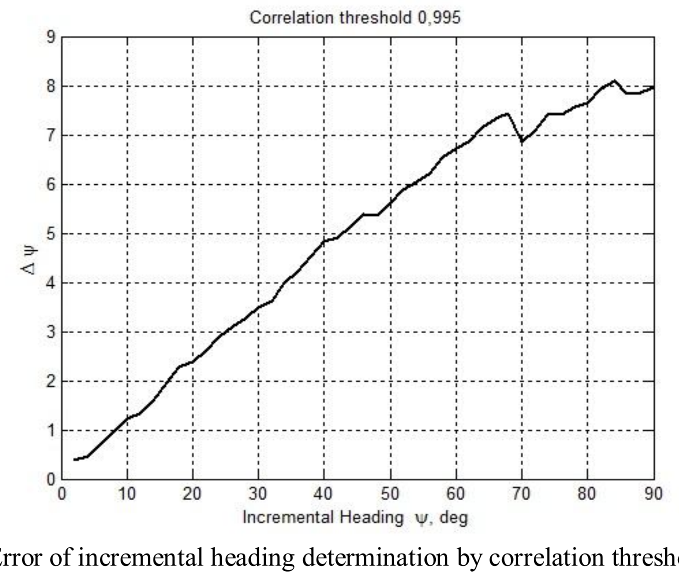


Fig. 9. Error of incremental heading determination by correlation threshold 0,995

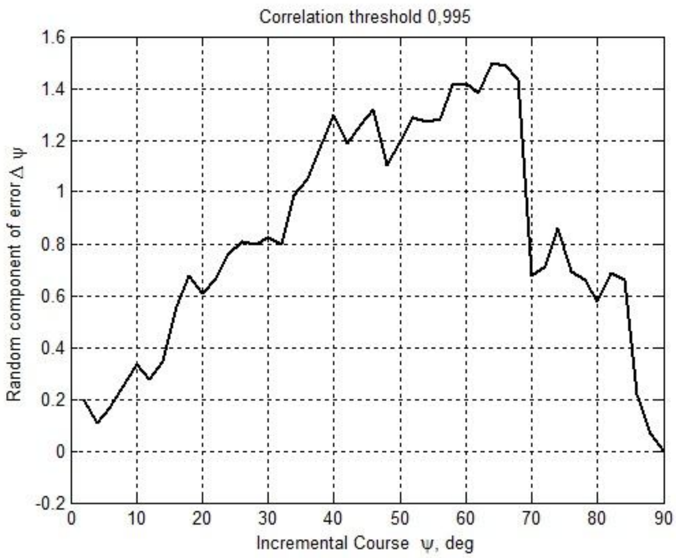


Fig. 10. Random component of incremental heading determination

By assuming the normal distribution of heading error $\Delta\psi$ it is possible to fit and obtain statistical characteristics of heading channel with mathematical expectation 0,8228 and variance 0,4402.

Thus, the error model of heading channel in vision-based correlation-extreme navigation system can be represented as follows:

$$\psi_{VCENS} = \psi + \Delta\psi + \xi_{\psi}, \quad (4)$$

where $\psi$ is true value f heading, $\Delta\psi$ is constant slow varied component of error, $\xi_{\psi}$ is random component of heading error distributed by normal law.

Mathematical model of heading channel (4) can be used in data fusion by combining heading data from IMU, magnetometers, etc.

## Conclusions

The proposed algorithm of incremental heading determination allows us to obtain heading data from visual correlation-extreme navigation system with minimum computer time consumption. Average time consumption for heading determination (without time required for SURF realization that significantly depends on the volume of compared images) is about 0,02 sec. Taking into account the obtained mathematical model of heading errors (4) the accuracy of heading determination can be reached up to ±0,4°, and significantly increase accuracy of complex correlation-extreme navigation system.

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## МОДЕЛЬ ПОХИБОК КАНАЛУ КУРСУ ВІЗУАЛЬНОЇ КОРЕЛЯЦІЙНО-ЕКСТРЕМАЛЬНОЇ НАВІГАЦІЙНОЇ СИСТЕМИ

*М. П. Мухіна*

Запропоновано алгоритм визначення курсу, що ґрунтується на кореляції пари зображень: базового з геоприв'язкою та поточного. Кореляція здійснюється між дескрипторами характерних точок, визначених за допомогою методу SURF. Як метрику похибок для співставлення пари зображень обрано нормалізований коефіцієнт кореляції з точки зору обчислювальної ефективності. Досліджено похибки визначення курсу для різних значень порогу нормалізованого коефіцієнту кореляції та запропоновано інкрементний підхід. Виділено постійну та випадкову складові похибки курсу та на основі нормального розподілу побудовано модель похибок каналу курсу візуальної кореляційно-екстремальної навігаційної системи.

**Ключові слова**: кореляційно-екстремальна навігація, метод прискореного знаходження робасних характерних ознак (SURF), нормалізований коефіцієнт кореляції.

## МОДЕЛЬ ПОГРЕШНОСТЕЙ КАНАЛА КУРСА ВИЗУАЛЬНОЙ КОРРЕЛЯЦИОННО - ЭКСТРЕМАЛЬНОЙ НАВИГАЦИОННОЙ СИСТЕМЫ

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Предложен алгоритм определения курса, основанный на корреляции пары изображений: базового с геопривязкой и текущего. Корреляция осуществляется между дескрипторами характерных точек, определенных с помощью метода SURF. В качестве метрики погрешностей для сопоставления пары изображений выбран нормализованный коэффициент корреляции с точки зрения вычислительной эффективности. Исследованы погрешности определения курса для различных значений порога нормализованного коэффициента корреляции и предложен инкрементный подход. Выделены постоянная и случайная составляющие погрешности курса, и на основе нормального распределения построена модель погрешностей канала курса визуальной корреляционно - экстремальной навигационной системы.

**Ключевые слова**: корреляционно - экстремальная навигация, метод ускоренного нахождения робастных характерных признаков (SURF), нормализованный коэффициент корреляции.

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