Algorithms of Aircraft Flight Parameters Determination via the Visual Data

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Abstract: This paper provides the information about the possibility of independent information channel development for determination of altitude, list and pitch of aircrafts based on the visual data analysis. All stages of solving the information support problem for aircraft control system based on the collection and processing of the visual data are considered here. This paper provides the information about the development of mathematical model, the calibration of visual fields and the provision of stereoscopic calculations accuracy. The mathematical support of the computer vision system, consisting of two video cameras and computing unit installed on the aircraft, is also described here. The proposed algorithms are implemented for the system model as a part of the flying laboratory. The results of the experiments carried out for this model are also presented here. The results allow drawing the conclusion about the possibility of successful solution of the problem. Possible ways for further system improvement are also presented in this paper.

1 INTRODUCTION

Achievements of video equipment, computer facilities, algorithmic of visual data acquisition and processing allow considering a question of creation economically expedient computer vision systems, for the solution of problems of aircraft control systems information support. Now a large number of developments of unmanned vehicle is developed. Vision systems as a part of systems of information support play the increasing role, especially at the solution of tasks in the conditions of uncertainty. Unmanned aerial vehicles get the increasing degree of autonomy. Messages on the solution of such tasks as automatic UAV takeoff and landing on an aircraft carrier, refueling of UAV in air are known (lenta.ru, 2012). Realization of VS advantages demands overcoming of a number of problems. Large volume of data which should be processed on the scale of real time demands powerful computing tools and effective processing algorithms.

In our work we decided to estimate a possibility of determination of height, a list and pitch of aircraft based on the visual data analysis. A practical inspection of the developed software was performed on the VS model which was established onboard of the flying laboratory.

2 ESTIMATION OF ERROR IN POINT HEIGHT DETERMINATION VIA STEREO IMAGES

The first step of studies was the estimation of the error, with which the flight altitude can be determined based on the visual data of the stereo system.

The scheme of calculation of an error of determination of altitude according to a stereosystem data is given in fig. 1. From the known formulas for stereosystems (Lobanov, 1984; Hartley and Zisserman, 2003) we will receive formulas for an error estimation.

1) The value of the stereo depth depending on the parallax: $Z = f \cdot s/P$, where Z is the stereo depth of the point (meters), f is the focal length (pixels), s is the stereo base (meters), P is the point parallax (pixels). Therefore, $\ln Z = -\ln P + C$, and $\frac{dZ}{Z} = -\frac{dP}{P}$. The relative error in the stereo depth determination is equal to the relative error in the parallax determination.

2) Substituting P from step (1) and omitting the error sign, we obtain $dZ = Z^2/(fs) \cdot dP$ or $\delta_z = Z^2/(fs)$ (considering that $dP = 1$ pixel) – the

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connection between the stereo depth Z and the error δ_z in its definition.
3) The error in the determination of the point position in the plan is equal to $\delta_p = Z/f$ – the size of single pixel in the plan at the depth Z.

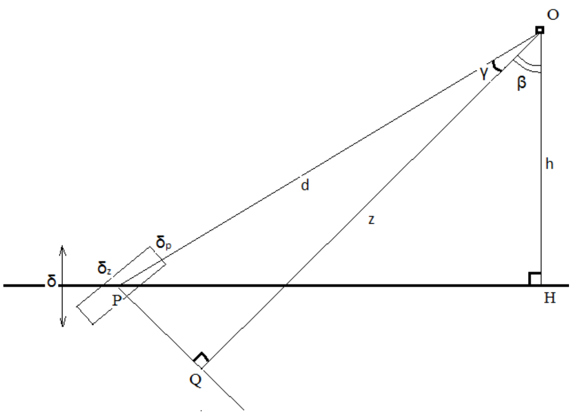


Figure 1: The scheme for calculating the altitude determination error via the stereo system data: O is the projection center, P is the point on the ground, H is the projection of the point O on the ground, PH is the ground (horizontal), $PH \perp OH$, OQ is the optical axis, $PQ \perp OQ$.

Let us denote $OH = h$, $OP = d$ is the range, $OQ = Z$– is the stereo depth of the point P. Then $Z = d\cos\gamma = h\cos\gamma/\cos(\beta+\gamma)$, and the formulas for errors in the depth and in the plan are

$$\delta_z = \frac{Z^2}{fs} = \frac{h^2}{fs} \cdot \cos^2\gamma\,/\cos^2(\beta+\gamma) \quad (1)$$

$$\delta_p = \frac{Z}{f} = \frac{h}{f} \cdot \cos\gamma/\cos(\beta+\gamma) \quad (2)$$

The error in the altitude determination is

$$\delta = \sqrt{\delta_z^2\cos^2\beta + \delta_p^2\sin^2\beta} \quad (3)$$

Here β is the angle of the optical axis inclination to the vertical (fixed), $\gamma = \mathrm{arctg}((y-y_0)/f)$, y is variable line number (pixels from 0 to 1200), y_0 is the fixed line number of the main frame point.

The graphs of the error dependence in determining the height of the point $\delta(y)$ on the image line number of y for different values of the shooting height h are shown below.

We used the data of the system model, on which the experiments were carried out (fig. 2 and Section 5), as qualitative values of the parameters. The parameters being used: The number of image lines is 1200. The focal length f = 1500 pixels. The main point in the 600th line (y_0 = 600). The stereo base s = 1,5 meters. The angle of the optical axis inclination to the vertical β = 75° (5π/12).

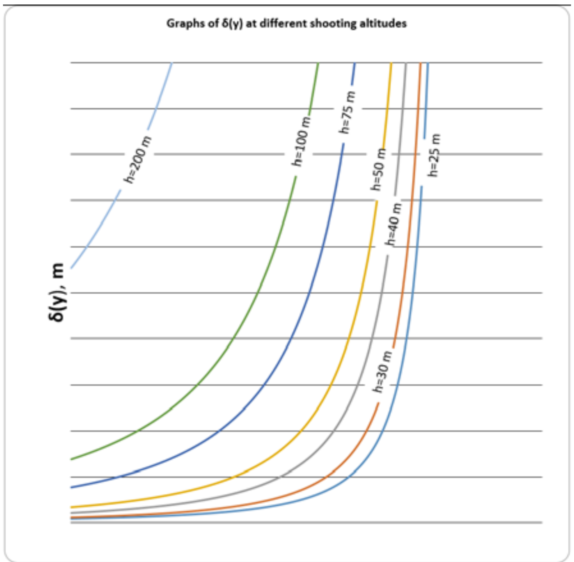


Figure 2: Theoretical graph of the altitude determination error dependence on the frame line number (the lines are numbered from the bottom up).

Therefore, some relevant information on the flight altitude can be obtained only when shooting at the altitude of not more than 150 m using the stereo pair with the stereo base of the order of 1,5 m and β = 75°.

3 CALIBRATION OF VIDEO CAMERAS

The calibration of fields of view (the orientation of video cameras) is the important stage in the computer vision system preparation for measurements. The orientation of video cameras includes internal orientation and external orientation. To calculate the parameters of internal and external orientation (calibration) we used our own program, similar to that available in OpenCV library (MatLab, 2016; OpenCV, 2016).

The calculation of internal orientation consists in determining the coordinates of the main frame point, the focal length and the distortion parameters. Images of a chessboard at various angles was used as initial data. Actually in calculating the internal orientation, when solving the corresponding system of equations, the residuals were about 0.7 pixels on average and 3 pixels maximum, that is the distortion was almost completely compensated.

External orientation consists in determining the projection matrix elements and the projection center coordinates for each camera in the aircraft coordinate system. One frame was used as initial data for each camera with marked reference points (points with previously measured 3D coordinates). The reference points were marked on the hangar floor so that not less than 4 points were in the vision field of each camera (13 points were used in total). Then they were manually assigned approximate coordinates with respect to the aircraft with the accuracy of 1 m. After that the pairwise distances between the points were measured using measure tape. Then the coordinates were defined by our own program using the least square method. The residuals in the determination of coordinates from the values of pairwise distances measurements were equal to 1 cm maximum and 0,3 cm on average.

The residuals in the calculation of external orientation were equal to 4 pixels on average and 7 pixels maximum. This result leaves much to be desired. The reason is that many of reference points of the frame were not clearly visible because of the glare. According to the calibration results the stereo base is 1,33 m.

4 MATHEMATICAL MODEL – CALCULATION FORMULAS FOR FLIGHT PARAMETERS DETERMINATION

We consider flat relief model as the approximation, i.e. we assume that the flight is carried out above the plane. At that the images for left and right cameras after correcting deviations caused by the distortion will be connected by some projective transformation. Let's additionally suppose that both images are obtained simultaneously. Then we can obtain the elements of the connective projective transformation matrix, depending on the coefficients of the ground plane equation, by recording the ground plane equation in the aircraft coordinate system with indefinite coefficients and knowing the parameters of external orientation of both cameras in the aircraft coordinate system. On the other hand, we can find some common points on left and right frames using the correlation and then find the connective projective transformation matrix by the least squares method after correcting the deviations of the points coordinates caused by the distortion. Now by making these two matrices equal to each other we obtain the overdetermined system of 9 equations (according to the number of matrix elements), from which we can find the desired ground plane equation the in the aircraft coordinate system, and thereby we obtain the estimation of the flight altitude and the angles of list and pitch of the aircraft.

Assume that f and f' are the focal lengths of left and right cameras in pixels. Assume that $\boldsymbol{o}$ and $\boldsymbol{o}'$ are the centers of left and right cameras projection in the aircraft coordinate system, $\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3$ and $\boldsymbol{e}'_1, \boldsymbol{e}'_2, \boldsymbol{e}'_3$ are basis unit vectors related to left and right cameras ($\boldsymbol{e}_1$ – in the frame line from left to right, $\boldsymbol{e}_2$ – in the column from top to bottom, $\boldsymbol{e}_3$ – from the camera to the object (orthogonally to the $\boldsymbol{e}_1\boldsymbol{e}_2$ plane). Assume that $\boldsymbol{e}$ and $\boldsymbol{e}'$are orthogonal matrices with the lines $\boldsymbol{e}_i$ and $\boldsymbol{e}'_i$ respectively (the projection matrices), $\boldsymbol{s} = \boldsymbol{o} - \boldsymbol{o}'$ is the stereo base vector.

Assume that $\langle \boldsymbol{p}, \boldsymbol{n} \rangle = z_0$ is the ground plane equation in the aircraft coordinate system, where $\boldsymbol{p} = (x, y, z)$ is variable spatial point, $\boldsymbol{n}$ is normal unit vector to the plane, $\langle \cdot, \cdot \rangle$ is the scalar product.

Assume that (X, Y) and (X', Y') are the pixel coordinates corrected for the distortion in relation to the main point on left and right frame respectively. Let us denote

$$P = \begin{pmatrix} X \\ Y \\ f \end{pmatrix} \text{ and } P' = \begin{pmatrix} X' \\ Y' \\ f' \end{pmatrix}.$$

Then the spatial points, projecting to the point (X, Y), lie on the straight line

$$\boldsymbol{p} = \boldsymbol{o} + t(X\boldsymbol{e}_1 + Y\boldsymbol{e}_2 + f\boldsymbol{e}_3) = \boldsymbol{o} + t\boldsymbol{e}^T P$$

Here T denotes the matrix transposition. This straight line intersects the ground plane when

$$t = \frac{z_0 - \langle \boldsymbol{o}, \boldsymbol{n} \rangle}{X\langle \boldsymbol{e}_1, \boldsymbol{n} \rangle + Y\langle \boldsymbol{e}_2, \boldsymbol{n} \rangle + f\langle \boldsymbol{e}_3, \boldsymbol{n} \rangle} = -\frac{h}{\langle \boldsymbol{e}^T P, \boldsymbol{n} \rangle}$$

Here $\langle \boldsymbol{o}, \boldsymbol{n} \rangle - z_0 = h$ is denoted as the distance from the point $\boldsymbol{o}$ to the ground plane. The condition that the point $\boldsymbol{p}$ is projected to the right frame at the point (X', Y') is written as follows: $\boldsymbol{e}' \cdot (\boldsymbol{p} - \boldsymbol{o}') = \mu \cdot P'$, where μ is the numerical factor. After that by substituting the expression for $\boldsymbol{p}$ we get:

$$\boldsymbol{e}' \cdot \left(\boldsymbol{o} - \frac{h}{\langle \boldsymbol{e}^T P, \boldsymbol{n} \rangle} \boldsymbol{e}^T P - \boldsymbol{o}' \right) = \mu \cdot P'$$

$$\boldsymbol{e}' \cdot (\boldsymbol{s}\langle \boldsymbol{e}^T P, \boldsymbol{n} \rangle - h\boldsymbol{e}^T P) = \mu \langle \boldsymbol{e}^T P, \boldsymbol{n} \rangle \cdot P'$$

$$(\boldsymbol{e}'\boldsymbol{s}(\boldsymbol{e}\boldsymbol{n})^T - h\boldsymbol{e}'\boldsymbol{e}^T)P = \mu \langle \boldsymbol{e}^T P, \boldsymbol{n} \rangle \cdot P'$$

$$(\boldsymbol{e}'\boldsymbol{s}(h^{-1}\boldsymbol{e}\boldsymbol{n})^T - \boldsymbol{e}'\boldsymbol{e}^T)P = h^{-1}\mu \langle \boldsymbol{e}^T P, \boldsymbol{n} \rangle \cdot P'$$

Therefore, the connective projective transformation matrix with the accuracy up to the proportionality coefficient is

$$\boldsymbol{e}'\boldsymbol{s}(h^{-1}\boldsymbol{e}\boldsymbol{n})^T - \boldsymbol{e}'\boldsymbol{e}^T = \boldsymbol{e}'\boldsymbol{s}\boldsymbol{u}^T - \boldsymbol{e}'\boldsymbol{e}^T$$

where the vector $\boldsymbol{u} = h^{-1}\boldsymbol{e}\boldsymbol{n}$ is the vector of length, which is equal to h^{-1} and proportional to the vector $\boldsymbol{n}$, factorized on the basis $\boldsymbol{e}_1, \boldsymbol{e}_2, \boldsymbol{e}_3$. Hence, we obtain the following matrix equation for the known matrix M of the connective projective transformation

$$\boldsymbol{e}'\boldsymbol{s}\boldsymbol{u}^T - \boldsymbol{e}'\boldsymbol{e}^T = \lambda M \tag{4}$$

with unknowns $\boldsymbol{v}$ and λ, from which we find the coordinates of the vector $\boldsymbol{v}$, solving the overdetermined system of 9 linear equations with four unknowns by the least squares method (4). After that we obtain the estimation of the flight altitude $h = 1/|\boldsymbol{u}|$ and the coordinates of the vector $\boldsymbol{n}$ in the aircraft coordinate system as $\boldsymbol{n} = h\boldsymbol{e}^T\boldsymbol{u}$. The estimations for the angles of list κ and pitch τ with the known $\boldsymbol{n}$ are obtained from the following condition

$$\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\kappa & \sin\kappa\\ 0 & -\sin\kappa & \cos\kappa\end{bmatrix}\begin{bmatrix}\cos\tau & 0 & -\sin\tau\\ 0 & 1 & 0\\ \sin\tau & 0 & \cos\tau\end{bmatrix}\begin{bmatrix}0\\0\\1\end{bmatrix} = \boldsymbol{n}$$

From which $\tau = -\arcsin n_x$, $\kappa = \arcsin\left(n_y/\sqrt{n_y^2 + n_z^2}\right)$, where $\boldsymbol{n} = \left(n_x, n_y, n_z\right)$

Let's make a remark about the summand $\boldsymbol{e}'\boldsymbol{e}^T$ in the matrix equation. For $h \to \infty$ we have $\boldsymbol{u} \to \boldsymbol{0}$. Therefore, $\boldsymbol{e}'\boldsymbol{e}^T$ is the connective projective transformation matrix for «infinitely high» flight altitude (at infinity). And $\boldsymbol{e}'\boldsymbol{s}\boldsymbol{u}^T$ is the correction, which is the greater, the smaller the flight altitude and the greater the stereo base.

5 DIFFICULTIES IN PRACTICAL IMPLEMENTATION OF FLIGHT PARAMETERS DETERMINATION

5.1 Synchronization of Left and Right Cameras Images

Without the special external device forming synchronization impulses in the shots received from video cameras the relative shift making units of shots is observed. When giving clock pulses from one of stereo pair camera on another shots are synchronized, but the frequency of delivery of these shots steadily decreases. Taking into account that the task of supply with information of a control system of the aircraft on a responsible site of landing – the movement on a glide path is set for VS, the decision to leave the maximum frequency of delivery of shots, and the found mismatches on time to compensate algorithmically, in processing of visual data was made.

The formulas of the previous paragraph are valid, if left and right frames are received strictly synchronized. Actually, this is not the case. The frames are received through the network independently from left and right cameras and can be out of sync for up to 0,2 seconds. During this time the plane is able to move to the distance much greater than the stereo base that was found during the calibration.

To compensate for this effect, we proceeded as mentioned below. At first, regular grid of points is recalculated by the correlation (Beklemishev, 2016) from the left frame to the right frame (fig. 6). At that processing the epipolar correspondence (Lobanov, 1984; Hartley and Zisserman, 2003), as a rule, is broken because of the desynchronization. For the point on the left frame, its correlation pair on the right frame does not lie on the epipolar calculated on the basis of external orientation data.

Then another regular grid of points is recalculated by the correlation from the previous frame of the right camera to the current frame of the right camera (fig. 7). According to these data after correcting the deviations of points coordinates caused by the distortion using the least squares method, the average projective transformation from the previous right frame to the current right frame is found. According to this transformation, the sparse optical flow is calculated on the right frame: the displacement vector is determined for each point.

Finally, a pair of points, which corresponds on correlations of left and right frame, is considered for known optical flow and built on the epipolar right frame. It corresponds to the point on the left frame. Then the point on the right frame is transferred along the optical flow to the epipolar. Therefore, the correspondence for each point on the left frame is determined in two stages: at first by the correlation, and then the found point is transferred to the epipolar along the optical flow (fig. 3, 4).

After that the connective projective transformation matrix M is being found on the built pairs of points from the left frame to the right frame, which is used for estimation of the flight altitude as described above.

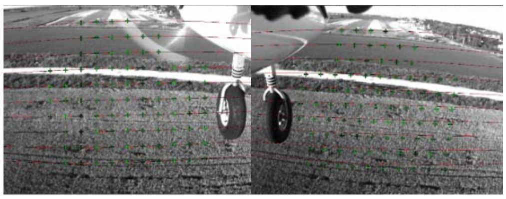
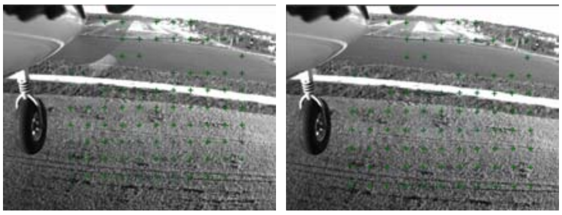


Figure 3: Points distributed along the regular grid on epipolar lines on the left frame and recalculated by the correlation to the right frame. The deviation of points from the epipolar on the right frame and the the epipolar deviation because of the lens distortion is notable.



(a) (b)

Figure 4: Regular grid of points recalculated by the correlation from the previous right frame to the current one.

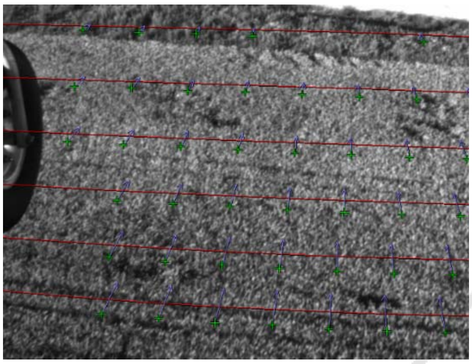


Figure 5: Points on the right frame recalculated by the correlation from the left frame and the optical flow.

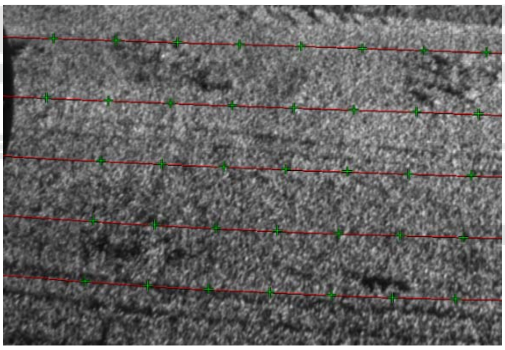


Figure 6: Points on the right frame recalculated by the correlation from the left frame and transferred to the epipolar by the optical flow.

5.2 Conditions of Image Capturing

It is not possible to align left and right images by the correlation, when image capturing occur in difficult conditions (landing against the sun (fig. 7), glare, landing above the terrain without contrasting details – snow, water).

Even at image capturing in good optical conditions when approaching the flight strip and flying over the flight strip, it is difficult to align the left and right frames due to the lack of contrasting details (fig. 11) at the top of the frame and because of the motion aberration at the bottom of the frame. In

Figure 7: The example of stereopair at the sunlight flash.

this case an improvement in the stereo algorithm is required, using the alignment of the selected edges of the flight strip.

Figure 8: The example of the complexity of images for analysis because of underlying terrain uniformity.

When the flight altitude is restored using the video example (glide-path capture, shooting at the altitude of 80-50 m, 1011 frames, 40 seconds of flight), there are emissions dependence on the frame number. These emissions are associated with aircraft maneuvers at glide-path capture. In such cases, the model for compensating the desynchronization of frames on the optical flow is no longer correct (fig. 9).

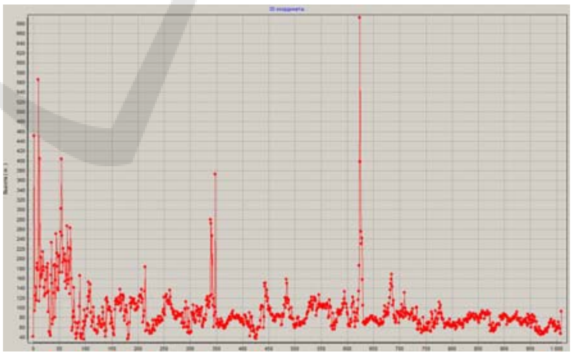


Figure 9: The errors of determination of flight altitude due to maneuvers of the aircraft.

6 RESULTS OF EXPERIMENTS

The described algorithms were tested on the visual data obtained by the vision system at the flying laboratory (fig. 13).

Figure 10: The Ikarus-C42 light plane onboard which the flying laboratory for studying of means of information support of aircrafts was organized.

Two video cameras ImiTech IMC-7020G were installed on board light aircraft Ikarus-C42 along the fuselage sides directed forward and down at the angle of about 75° to the vertical with the stereo base of about 1,3 m. The resolution of the cameras is 1600x1200 pixels, the frequency is 25 frames per second, the focal length is about 1600 pixels (the span angle is about 60°). The data were transmitted to on-board computer Compulab IntensePC via Gigabit Ethernet and recorded on the hard disk as uncompressed AVI-file with resolution of 3200x1200 pixels. Each frame of the recorded video consisted of adjacent frames of left and right cameras that were transmitted simultaneously.

Simultaneously with the recording of the video data the recordings of the integrated GPS receiver SBG IN-500 (SBG Systems, 2017) installed on board the flying laboratory have been fixed as well. This device allows you to fix the position and orientation of the aircraft with high accuracy.

Moreover, it has got a built-in barometric height sensor. These data were used for comparative analysis of measurement results based on visual data. The unified software framework of realtime vision systems developed by authors was the basis for software implementation of the described algorithms. This framework allows to increase efficiency of the development process of an applied vision system. Distinctive features of the offered approach to VS software developing are (Boguslavsky, 2003; Sokolov, 2016).

- The VS software architecture provides a possibility of cross-platform development on the basis of universal personal computers and fast transfer on special computing platforms due to software decomposition into a set of the interacting parallel subsystems.
- The extendable subsystem of visual data processing from several fields of view providing processing in real time of video sequences from visual sensors of high resolution.
- Using of reusable software components for visual data processing for the software prototyping.
- Implementation of special debugging means for ensuring reproducibility of software functioning at a development stage and at a trial stage.

6.1 Measurement

The following graphs (fig. 11-13) show the results of calculations of the flight parameters of an aircraft based on the processing of visual data (according to the formulas from Section 4).

For comparative analysis, the same graphs show data from an integrated SBG receiver (SBG Systems, 2017).

As a demonstration site, data were selected for the landing glide path from a height of 40 to 4 m (1011 frames, 40 seconds of flight).

The frame number changes from 0 to 970. The last 40 frames could not be processed due to the poor performance of the stereo algorithm while approaching the runway, see Section 5.2).The frame number changes from 0 to 970.

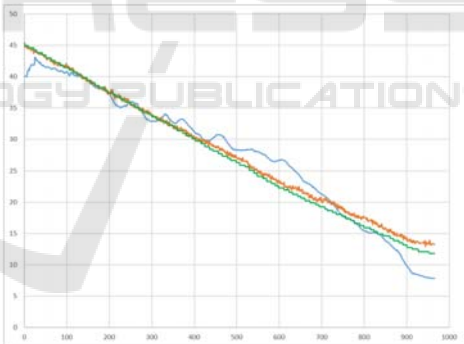


Figure 11: The altitude chart of the aircraft (in meters), depending on the frame number obtained by processing the visual data in comparison with the data of the integrated GPS receiver. The blue line is the height according to the visual data; Orange line – data of the barometric sensor from the SBG receiver, green line – height according to the GPS data of the SBG receiver.

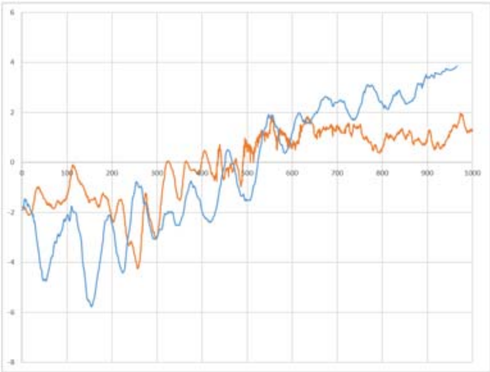


Figure 12: Graphs of the dependence of pitch (in degrees), depending on the frame number. The blue line is pitch, calculated on the basis of visual data processing; Orange line - pitch according to the integrated GPS receiver.

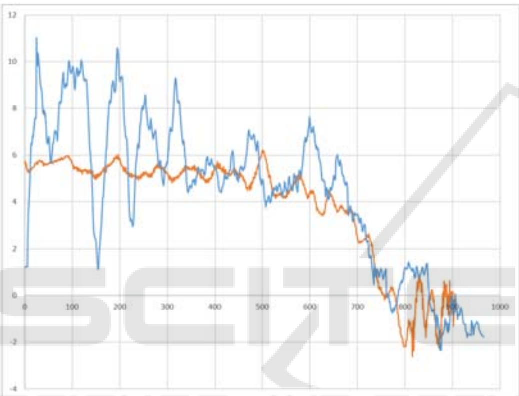


Figure 13: Graphs showing dependencies of roll (in degrees), depending on the frame number. The blue line is the bank, calculated on the basis of visual data processing; Orange line – roll according to the integrated GPS receiver.

6.2 Dependence of Time and Accuracy of Calculations on the Quality of Fields of View Alignment

The running time of the algorithm on the desktop PC Pentium Dual-Core CPU 3,06 GHz at one processor core is 0,18 seconds per frame (without considering the time of frame loading into the memory). A computer with these characteristics was installed on board a flying laboratory. With its help, visual data was collected and processed from a stereopair.

The processing of frames is carried out independently. Only the current left and right frames and the previous right frame are required to calculate the values of altitude, list and pitch. Therefore, even real-time processing of frames at the rate of 25 frames per second is achievable, in principle.

This running speed is achieved by recalculating regular grid of points (from the left frame to the right frame and from the previous right frame to the current right frame) by the correlation of 100 pixels in row and column. At that 917 of 1011 frames (90.7%) were processed. For others the correlation was estimated by the program as unreliable. When calculating the rarer grid, the running time is reduced, as is the quality of the result. Figure 14 shows the graph of the altitude change obtained by using the grid step of 200 pixels. At this step, 826 of 1011 frames (81.7%) were processed and the algorithm running time was 0,048 seconds per frame without considering the time of frame loading into the memory.

Figure 15 shows the graph of the altitude change obtained by using the grid step of 50 pixels. At the such step, 939 of 1011 frames (92.8%) were processed and the algorithm running time was 0,676 seconds per frame, without considering the time of frame loading into the memory.

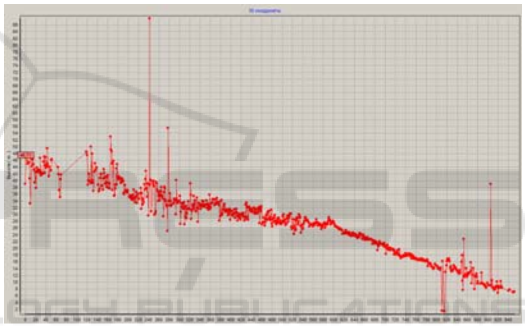


Figure 14: The graph of the altitude change depending on the frame number, the grid of points with the step of 200 pixels.

Figure 15: The graph of the altitude change depending on the frame number, the grid of points with the step of 50 pixels.

7 FURTHER RESEARCH

As it was noted in Section 5, practical realization of the offered approaches revealed a number of problems. Some from them were overcome, and a set only demand the decision.

To improve the performance of the flight parameters analyzer in the sunlight flash conditions. It is planned to use the lens screen.

To improve the performance of the correlator when shooting at low altitude on approaching the flight strip and when flying over the flight strip. It is planned to use the marking of the flight strip boundaries and other objects (fig. 16).

It is planned to use the marking of the horizon line on the frame to obtain the estimation of the current angles of list and pitch of the aircraft (fig. 16).

Synchronization of work of all algorithms taking into account the scale of real time is carried out by a large-scale framework of real time vision system software (Sokolov, 2016).

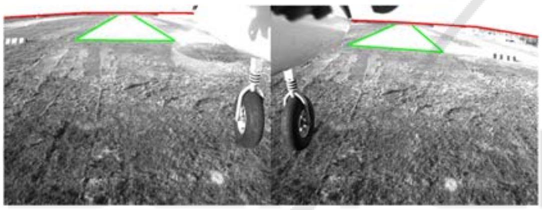


Figure 16: Example of definition of a line of horizon and runway borders in stereosystem fields of view.

To improve the accuracy of the flight parameters analyzer. It is possible to use a synchronous pair of video cameras, as well as more accurate calibration of the stereopair in terms of external orientation.

Also in this case it is possible to exclude the use of flat terrain model, provided that there is the matrix of altitudes, which was previously received and binded to the photographic plan.

8 CONCLUSIONS

The optical subsystem consisted of two video cameras directed forward and down at the angle of 75° to the vertical with the stereo base of about 1,5 meters in good visibility conditions allows obtaining stable estimation of the flight altitude, list and pitch when flying in straight line at the altitude from 150 to 0 meters. Such subsystem can be useful for automatic landing of unmanned aerial vehicles in good visibility conditions.

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REFERENCES

News agency lenta.ru The USA have finished UAV X-47B deck tests. URL http://lenta.ru/news/2012/12/20/x47b/

Lobanov, A.N., 1984. *Photogrammetry*, “Nedra”. Moscow, 552 pg.

Richard Hartley and Andrew Zisserman (2003). Multiple View Geometry in Computer Vision. Cambridge University Press. pp. 155–157. ISBN 0-521-54051-8.

Camera Calibration Toolbox for Matlab URL http://www.vision.caltech.edu/bouguetj/calib_doc

OpenCV, 2016. *OpenCV Library*, URL http://www.opencv.org

Beklemishev, N.D., 2016. Estimation of average parallax of stereo images. In *Preprints of M.V. Keldysh Institute of Applied Mathematics*, No. 88, 12 pg. http://library.keldysh.ru/preprint.asp?id=2016-88.

Boguslavsky A.A., Sokolov S.M. Component Approach to the Applied Visual System Software Development. 7th World Multiconference on Systemics, Cybernetics and Informatics (SCI 2003), July 27-30, Orlando, Florida, USA, 2003

Sokolov S.M., Boguslavsky A.A. Layout for the information support system for mobile vehicles based on the real time vision system. // Proc. The 7th International Multi-Conference on Complexity, Informatics and Cybernetics: IMCIC 2016, March 8-11, 2016, Orlando, Florida, USA, pp. 243-247.

SBG Systems, 2017. *IG-500N: GPS aided miniature INS*. URL https://www.sbg-systems.com/products/ig500n-miniature-ins-gps