A REAL-TIME PHOTOGRAMMETRIC ALGORITHM FOR SENSOR AND SYNTHETIC IMAGE FUSION WITH APPLICATION TO AVIATION COMBINED VISION

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ABSTRACT:

The paper addresses a promising visualization concept related to combination of sensor and synthetic images in order to enhance situation awareness of a pilot during an aircraft landing. A real-time algorithm for a fusion of a sensor image, acquired by an onboard camera, and a synthetic 3D image of the external view, generated in an onboard computer, is proposed. The pixel correspondence between the sensor and the synthetic images is obtained by an exterior orientation of a "virtual" camera using runway points as a geospatial reference. The runway points are detected by the Projective Hough Transform, which idea is to project the edge map onto a horizontal plane in the object space (the runway plane) and then to calculate intensity projections of edge pixels on different directions of intensity gradient. The performed experiments on simulated images show that on a base glide path the algorithm provides image fusion with pixel accuracy, even in the case of significant navigation errors.

1. INTRODUCTION

Information support of a pilot during approach and landing in poor visibility still remains among the important tasks associated with the improvement of the safety and the efficiency of the flight. In the recent years the advance in the performance of onboard computers in the field of two-dimensional (2D) and three-dimensional (3D) visual data processing has led to emergence of a promising display concept for pilot assistance – Combined Vision System (CVS) (Thurber, 2011).

CVS is related to combination of sensor and synthetic images. The sensor image is acquired by an onboard camera, usually infrared. It allows a pilot to see the actual out-the-cabin situation, including dynamic obstacles. But an information content of the sensor image is highly dependable on the current visibility conditions. The synthetic image is a 3D "ideal" view of the terrain and geomapped objects along the flight path. It is generated through the use of navigation data and onboard databases of terrain, objects, and textures.

CVS fuses sensor and synthetic images to provide advantages of both, namely to increase flight visibility of unmapped objects (e.g. vehicle on a runway) from the sensor image and to see the most important visual keys of the airport's infrastructure (e.g. runways, buildings) as they are seen in ideal visibility conditions from the synthetic image.

To create the CVS image a problem of sensor and synthetic image matching must be solved, since the latter is generated by relying on navigation parameters of an aircraft, which are measured with errors.

One possible approach is to find the correspondence between the sensor and the synthetic image through the use of computer vision methods, and then to stabilize images by minimizing the displacement of matched pixels (Hamza, 2011). The limitation of this approach appears when the synthetic image is generated using a symbolic representation of real objects or synthetic terrain textures. In this case it is more likely that the matching procedure will fail. Also, the stabilization procedure can lead to negative visual effects due to space shifting and rotation of an image and takes additional computation time.

The paper represents different approach to the sensor and the synthetic images fusion that is based on a photogrammetric method and requires only analysis of the sensor image.

2. SENSOR AND SYNTHETIC IMAGE FUSION BASED ON PHOTOGRAMMETRIC METHOD

The basic idea of the represented approach is, firstly, to compute exterior orientation parameters of "virtual" camera using reference points of known geospatial coordinates, and only then to create the synthetic image which exactly matches to the sensor image because of compensated navigation errors.

The formal statement of the problem is formulated as follows: the exact position of the onboard camera is given by the unknown vector of the external orientation:

$$\boldsymbol{v_r} = (x_r, y_r, z_r, \theta_r, \gamma_r, \psi_r), \qquad (1)$$

where (x_r, y_r, z_r) – coordinates of the aircraft,
$(\theta_r, \gamma_r, \psi_r)$ – orientation vector of the aircraft.

The current camera position measured with some errors using the information from the navigational system of the aircraft is given by

$$\boldsymbol{v_e} = (x_e, y_e, z_e, \theta_e, \gamma_e, \psi_e) \qquad (2)$$

where (x_e, y_e, z_e) – coordinates of the aircraft in the geodesic coordinate system, received from the satellite navigation system,
$(\theta_e, \gamma_e, \psi_e)$ – vector of aircraft's pitch, roll, yaw angles.

Let $I_r = I(\boldsymbol{v_r})$ be the image acquired by the onboard camera.

The task is to find $\boldsymbol{v_r}$ by known $\boldsymbol{v_e}$ and I_r, and then generate $I_s(\boldsymbol{v_r})$ image, using available 3D-model M of the scene.

Since CVS is supposed to operate during the landing phase, the exterior orientation procedure can be performed using points of aerodrome infrastructure objects. In current version of the algorithm the runway points are considered as geo reference.

3. RUNWAY DETECTION

This paper proposes a runway detection algorithm, which is based on the Projective Hough Transform (PHT) (Komarov, 2012).

The idea of the PHT is to project edge map of the image onto a horizontal plane in object space (the runway plane) and then to calculate intensity projections of edge pixels on different directions of intensity gradient. The assumption is made that the runway longitudinal edges met close to the point of the observed horizon line. Figure 1 illustrates the parameterization (x_1, x_2) of PHT. The rotation of runway middle line in the runway plane corresponds to moving the vanishing point along the horizon. The shift of the middle line to the left or to the right in the runway plane corresponds to a shift of x_2 along the bottom line of the image.

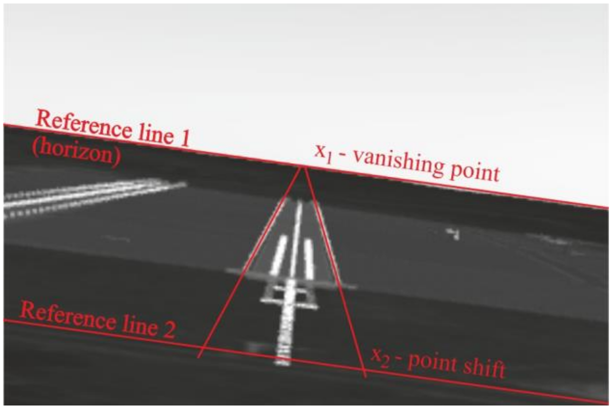


Figure 1. Parameterization of the Projective Hough Transform (x_1, x_2)

A quite similar parameterization is used in (Miller, 2008) for runway detection related to the task of the autonomous landing of an Unmanned Aerial Vehicle (UAV). The parameters are a point at the beginning of the runway (the spot where the UAV should touch down), and the vanishing point on the horizon made by the centerline of the runway. Three geometric properties are measured using this parameterization, the runway offset, the runway angle, and the runway distance. But the approach of the runway detection differs, and is based not on recognition of visual features of the runway itself, as is proposed in this paper, but on matching sensor images with a stack of reference images with a known runway location.

PHT parameterization requires the knowledge of the horizon position. In (Komarov, 2012) this position is found by the classical Hough Transform. The paper proposes the modification that uses navigation information to increase the performance and robustness in the case of low sky/earth contrast or non-observable horizon.

Figure 2 presents the geometrical estimation of the horizon position with navigation information support. Parameters are: f = focal length of the onboard camera, ΔH = shift of the horizon from the image center, θ = pitch of the aircraft, β_{hor} = angle between the horizon line and the main optical axes.

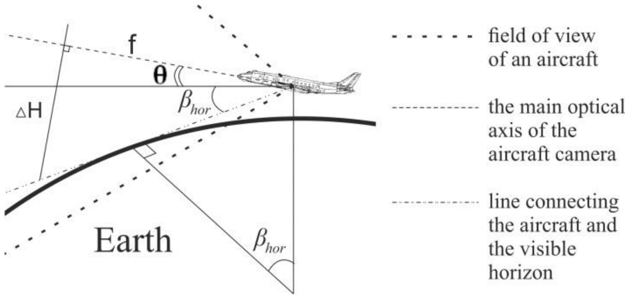


Figure 2. Geometrical estimation of the horizon position with navigation information support

Angle between the horizon line and the main optical axis in the case of zero pitch is found as:

$$\beta_{hor} = arccos\left(\frac{R_{Earth}}{R_{Earth}+H_{aircraft}}\right) \quad (3)$$

where R_{Earth} = radius of the Earth;
$H_{aircraft}$ = height of the aircraft.

Vertical shift of the horizon from the image centre is calculated as:

$$\Delta H = f \cdot tg(\theta + \beta_{hor}) \quad (4)$$

The resulting position of the horizon line in the image coordinate system is found by the rotation through the row angle.

After that, the primary estimation of the vanishing point is performed. The image coordinates of the runway in pixels are given by the following equation:

$$x_{pxl} = f\frac{D_x}{D_z} + b_x;\ y_{pxl} = -f\frac{D_y}{D_z} + b_y \quad (5)$$

where b_x, b_y = image coordinates of the principal point in pixels;
D_x, D_y, D_z = coordinates of runway points in the aircraft's coordinate system. They could be found as following:

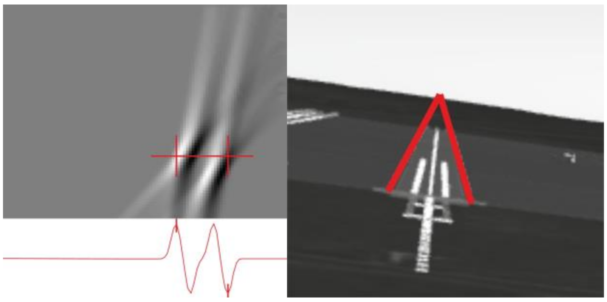
$$\begin{pmatrix} D_x \\ D_y \\ D_z \end{pmatrix} = A(\theta,\gamma,\psi) \cdot \begin{pmatrix} x_p - x_f \\ y_p - y_f \\ z_p - z_f \end{pmatrix} \quad (6)$$

where x_p, y_p, z_p = coordinates of the reference point;
x_f, y_f, z_f = coordinates of the aircraft;
$A(\theta,\gamma,\psi)$ = rotation matrix.

Longitudinal edges of the runway are extended to the intersection with the horizon line. The vanishing point is defined as the mean of coordinates of points of intersection.

The following processing is restricted to the areas defined by longitudinal edges of the runway and the vanishing point. This helps to exclude from the processing the areas where runway cannot be located (e.g. the sky).

To find the longitudinal edges of the runway the derivative of PHT accumulator in horizontal direction is found (fig. 3, a, upper). The row with the symmetrical local extremums of maximal amplitude (fig. 3, a, lower) gives the coordinates of the vanishing point, and position of extremums in the row corresponds to the positions of the left and the right borders of the runway respectively (fig. 3, b).

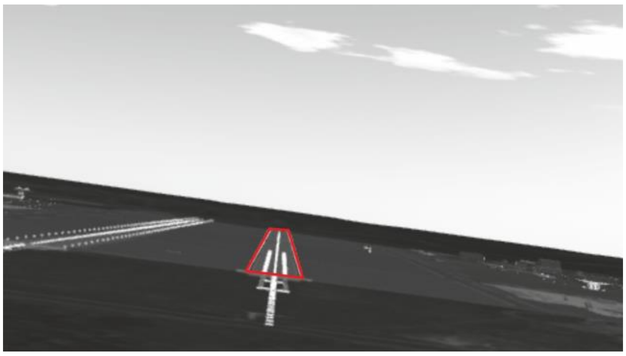


(a) (b)

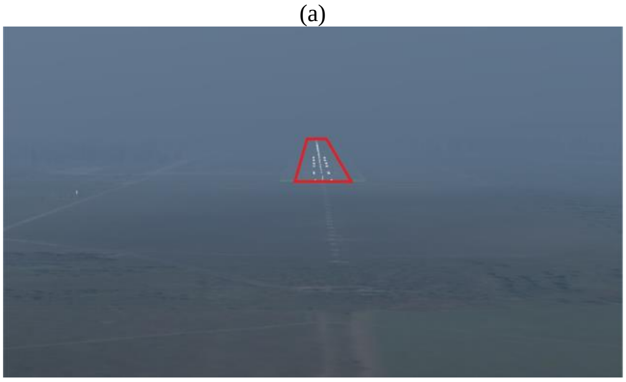
Figure 3. A search of longitudinal edges of the runway: (a, upper) – derivative of PHT accumulator in horizontal direction, (a, lower) – profile of the row with the symmetrical local extremums of maximal amplitude, (b) – the left and the right borders of the runway corresponding to the extremums

To determine the position of the top and the bottom runway edges, the assumption is used that the runway image area is brighter than the surrounding background. The edges correspond to the most significant value changes on the projection of intensity values are taken inside the longitudinal line triangle. Reference points are given as the points of intersection of longitudinal edges of the runway with the top and the bottom edges.

Figure 4 illustrates examples of the runway detection in different conditions on simulated images.



(a)



(b)

Figure 4. Examples of the runway detection in clear visible conditions (a) and in fog (b)

4. EXTERIOR ORIENTATION OF THE CAMERA

An initial position of the virtual camera is defined by navigation parameters of the aircraft. The exterior orientation algorithm elaborates the elements of rotation matrix, which sets the virtual camera angles relative to the Earth coordinate system. The task is solved by minimizing the residual of collinearity equations taken for the projection center, the reference points and the corresponding points on the image.

The current version of the orientation algorithm allows using features of multiple runways as reference points. The number of points N is given by formula:

$$N = 4k \tag{7}$$

where k = number of runways in the field of view of the aircraft's camera.

Since the algorithm is designed to work in poor visibility conditions feature points of the runway lightning could be used as additional reference points. Such points are detected using the Harris detector (Harris, 1988). In this case during the external orientation process the weight matrix is used. Smaller weights are given to the additional reference points.

The modern onboard satellite navigation systems provide the position coordinates of the aircraft that are accurate enough for modeling during the landing stage. The error in the position does not affect the quality of the registration of synthesized and sensor images. Thanks to this it is needed to refine only pitch, roll and yaw angles of the aircraft.

The problem is solved iteratively by least squares approximation with the given initial value of the rotation matrix A. The estimated parameters at each step of the iteration are: $\Delta\alpha$, $\Delta\omega$, $\Delta\kappa$ angles. They define the rotation around the axes of the image coordinate system. New values of the elements of the matrix A are found at the each step of the iteration:

$$A_{i+1} = \Delta M(\Delta\alpha, \Delta\omega, \Delta\kappa) A_i \tag{8}$$

where i = number of iteration;

$$\Delta M(\Delta\alpha, \Delta\omega, \Delta\kappa) = \Delta M(\Delta\alpha)\Delta M(\Delta\omega)\Delta M(\Delta\kappa) \tag{9}$$

where $\Delta M(\Delta\alpha), \Delta M(\Delta\omega), \Delta M(\Delta\kappa)$ = rotation matrices that give rotation around the axes of the image.

Since angles $\Delta\alpha$, $\Delta\omega$, $\Delta\kappa$ are small the cosine values could be taken as 1.0, and sine values are equal to corresponding angles. For example, for the rotation matrix $\Delta M(\Delta\alpha)$:

$$\Delta M(\Delta\alpha) = \begin{pmatrix} \cos(\Delta\alpha) & 0 & \sin(\Delta\alpha) \\ 0 & 1 & 0 \\ -\sin(\Delta\alpha) & 0 & \cos(\Delta\alpha) \end{pmatrix} \cong$$
$$\cong \begin{pmatrix} 1 & 0 & \Delta\alpha \\ 0 & 1 & 0 \\ -\Delta\alpha & 0 & 1 \end{pmatrix} \tag{10}$$

To estimate the $\Delta\alpha$, $\Delta\omega$, $\Delta\kappa$ it is needed to find partial derivatives of elements of the rotation matrix M with respect to $\Delta\alpha$, $\Delta\omega$, $\Delta\kappa$:

$$\frac{\partial M}{\partial \Delta\alpha} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \end{pmatrix}; \tag{11}$$

$$\frac{\partial M}{\partial \Delta\omega} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{pmatrix}; \tag{12}$$

$$\frac{\partial M}{\partial \Delta\kappa} = \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}; \tag{13}$$

Residuals in the image plane are given by formulas:

$$(e_x)_j = x_j - f\frac{(D_x)_j}{(D_z)_j}; \tag{14}$$

$$(e_y)_j = y_j - f\frac{(D_y)_j}{(D_z)_j}; \tag{15}$$

where x, y = coordinates of reference points detected in the image.
j = number of the reference point.

Then, for example for the angle $\Delta\alpha$, partial derivatives of residuals are given by:

$$\left(\frac{\partial e_x}{\partial \Delta\alpha}\right)_j = (d_x)_j + \frac{x_j}{f}(d_z)_j; \tag{16}$$

$$\left(\frac{\partial e_y}{\partial \Delta\alpha}\right)_j = (d_y)_j + \frac{y_j}{f}(d_z)_j; \tag{17}$$

$$\begin{pmatrix} d_x \\ d_y \\ d_z \end{pmatrix}_j = \frac{\partial M}{\partial \Delta\alpha}\begin{pmatrix} x_j - x_s \\ y_j - y_s \\ z_j - z_s \end{pmatrix}; \tag{18}$$

where x_j, y_j, z_j = coordinates of reference points in the photogrammetric coordinate system;
x_s, y_s, z_s = coordinates of the projection center in the photogrammetric coordinate system.

Matrix of partial derivatives of residuals is given by:

$$B = \begin{pmatrix} \cdots & \cdots & \cdots \\ \left(\frac{\partial e_x}{\partial \Delta\alpha}\right)_j & \left(\frac{\partial e_x}{\partial \Delta\omega}\right)_j & \left(\frac{\partial e_x}{\partial \Delta\kappa}\right)_j \\ \left(\frac{\partial e_y}{\partial \Delta\alpha}\right)_j & \left(\frac{\partial e_y}{\partial \Delta\omega}\right)_j & \left(\frac{\partial e_y}{\partial \Delta\kappa}\right)_j \\ \cdots & \cdots & \cdots \end{pmatrix}; \tag{19}$$

Residual vector is given by:

$$l_0 = \begin{pmatrix} \cdots \\ (e_x)_j \\ (e_y)_j \\ \cdots \end{pmatrix}; \tag{20}$$

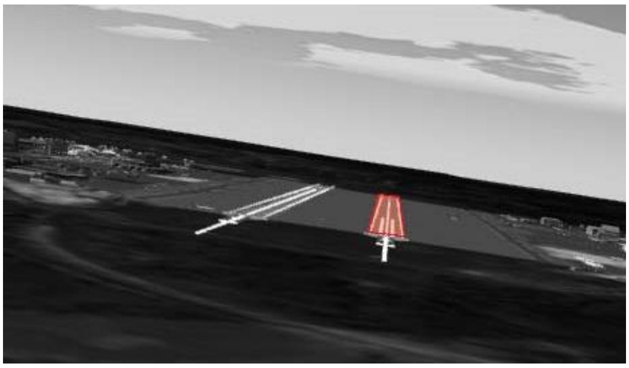
Angles $\Delta\alpha$, $\Delta\omega$, $\Delta\kappa$ are given by:

$$\begin{pmatrix} \Delta\alpha \\ \Delta\omega \\ \Delta\kappa \end{pmatrix} = (B^T B)^{-1} B^T l_0 \tag{21}$$

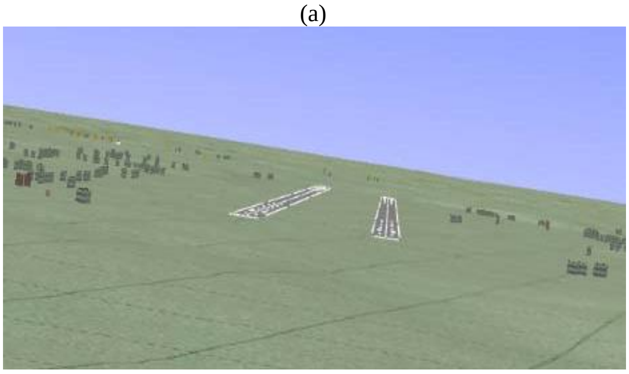
5. EXPERIMENTAL RESULTS

The algorithm was verified using the computer simulation. The aircraft flight area and conditions (underlying relief, buildings, moving ground and aerial vehicles, meteorological conditions, time of the day, atmospheric conditions, sky background and special effects) were simulated using the External Data Simulation System (EDSS). The EDSS also provides the simulation of video output of onboard camera.

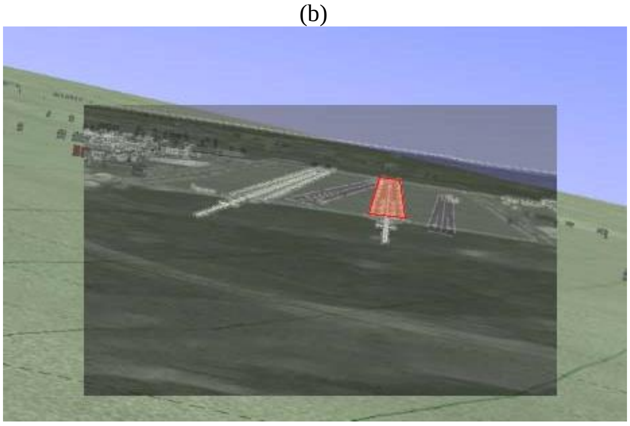
Figure 5 illustrates example of the algorithm testing (see the text for explanation).



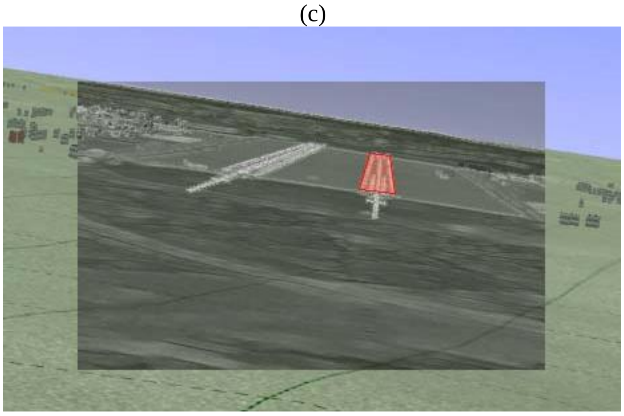
(a)



(b)



(c)



(d)

Figure 5. Testing of the algorithm by means of computer simulation: a) modeled TV image (fragment) and the result of the runway detection; b) SVS image;

c) combination of TV and SVS images without exterior orientation; d) combination of TV and SVS images after exterior orientation. The runway is highlighted to assess their differences (c) and overlap (d).

The landing stage was modelled for the base glide path of the aircraft. The algorithm was activated after the appearance of the runway in the camera's field of view.

The following input data was used for the algorithm: the simulated sensor image of the out-the-cabin environment (fig. 5, a); coordinates of runway edges in the image and geodetic coordinate systems; current pitch, roll and yaw of the aircraft from the dynamical model of the aircraft with added errors.

The synthetic image (fig. 5, b) was generated by the prototype of synthetic vision function (SVS) using the input data from the navigational system of the aircraft and digital terrain model.

Figure 5,c illustrates the example of the sensor and synthetic image combination without external orientation. The error in the image space is about 100 pixels for the modelled errors of -3 degree in pitch angle and +5 degree in roll angle.

After the process of the external orientation the refined values of pitch, roll and yaw angles were used by the SVS function. The combination of the sensor and new synthetic images is shown on figure 5,d.

During the tests on the base glide path, the fusion algorithm provided error of the sensor and the synthetic images combination with pixel accuracy that is sufficiently for comfortable perception of the visual data by a pilot.

6. CONCLUSIONS

An algorithm for sensor and synthetic image fusion for aviation Combined Vision System is proposed. The algorithm is based on an exterior orientation of virtual camera through the use of runway points. The runway points are detected on the sensor image by the Projective Hough Transform with the support of the navigation information. The algorithm was verified by ground experiments using simulated images on a base glide path.

Currently, the algorithm's limitation is connected with the assumption that the runway bounds are available on the sensor image, which might not always be true due to occlusion. The further work to improve the algorithm robustness includes the development of model-based vision methods for the automatic detection and identification of not only the runway but other types of airfield infrastructure objects as well.

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