# ENHANCED AND SYNTHETIC VISION SYSTEMS DEVELOPMENT BASED ON INTEGRATED MODULAR AVIONICS

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## Abstract

*The paper describes the current results of a research and development (R&D) project aimed to create the advanced prototypes of Enhanced Vision System and Synthetic Vision System with such distinctive features as intellectual video analysis and scalable architecture based on Integrated Modular Avionics (IMA). The project is being performed by Russian State Research Institute of Aviation Systems (FGUP GosNIIAS) as a part of more complex R&D program for the IMA systems development.*

## 1 Introduction

These days the perspective of aviation safety improvement is closely tied with the development of novel avionics solutions, aimed to enhance flight visibility and situation awareness of a pilot. Such solutions include Enhanced Vision System (EVS) and Synthetic Vision System (SVS).

EVS uses optical sensors (first of all, infrared cameras) and image processing algorithms to expand the pilot capability to see the most important visual keys of aerodrome structure (e.g. runway lights). SVS creates a 3D textured image of the terrain and mapped objects along the pilots view through the use of navigation data, terrain, objects, and textures databases.

Also, the recent years advance in EVS and SVS technologies has led to the emergence of another promising display concept – combination of EVS and SVS, namely Combined Vision System (CVS). The CVS has both advantages of EVS to see the unmapped obstacles and SVS to provide the ideal visibility of terrain and mapped objects.

These days, there are a number of commercial EVS and SVS systems that have successfully passed the certification stage. A short list of companies, whose systems are already available on aircrafts, includes Rockwell Collins Inc., Thales, Honeywell Aerospace, Max-Viz Inc., CMC Electronics Inc., Selex Galileo, Chelton Flight Systems, Universal Avionics. Also, government agencies, industry and universities in leading aviation countries are pursuing numerous R&D programs for the further development of EVS, SVS, and CVS.

To ensure the competitiveness of Russian avionics solutions, FGUP GosNIIAS, under its complex program for IMA development [1], initiated an R&D project to create scientific and technological bases for the development of the advanced prototypes of EVS and SVS.

The project started in 2010 and this paper represents some results obtained by the middle of 2014.

## 2 EVS/SVS Hardware and Platform Overview

### 2.1 EVS Sensors

The EVS prototype will use multi-spectral optical-electronic system with three channels (Fig. 1): visible (TV), Short Wavelength InfraRed (SWIR), and uncooled Long Wavelength Infrared (LWIR).

**Fig. 1. The model of EVS optical unit (top) and the photo of EVS sensors (bottom)**

When choosing this set of channels, not only the energy and spectral characteristics were taken into account, but also the final weight, size and cost of optical unit as well.

The presence of the TV sensor is largely explained by the need to provide to a pilot a familiar view of out-cabin space in good visibility conditions, when it cannot be observed through the window (for example, in the case of icing). The SWIR channel provides a good visibility of an important airfield feature – runway lights, in bad weather, and at night. Motivation for the uncooled LWIR sensor is a good sensitivity in fog. The fulfilled experiments of IR-channels informativity estimation have shown that there are no decisive advantages between cooled HgCdTe/InSb Mid-wavelength infrared (MWIR) or LWIR sensors and uncooled LWIR. However, the latter sensor has a much lower cost and size.

Specification of the EVS optical unit includes:

- Size – 250mm (D) x 200mm (W) x 100mm (H).
- Weight – not exceeding 3 kg.
- Image dimensions – at least 640 x 512 pixels.
- Field of view (FOV) – at least 40° (H) x 30° (V).
- ARINC 818 output support.
- Video and service data recording.

The prototype of EVS optical unit is at the last stage of the development by Quantum Optical Systems Co. Ltd. (Russian Federation) and will have been ready for tests by August 2014.

## 2.2 EVS/SVS Platform

The EVS and SVS computer platform was developed by the Joint Stock Company «Scientific Design Bureau of Computer Systems» (Russian Federation).

This is an open distributed system based on VPX 3U IMA modules [2–3]. EVS occupies one slot in the IMA crate. So does the SVS. EVS computational resource consists of one Digital Image Processing Module with ARINC-818 support mezzanine. SVS task is performed by one Universal Central Processing Module with Graphic Processor Mezzanine. Inter-module communication is provided by the backplane via PCI Express expansion bus.

## 3 EVS/SVS Functional Requirements

Functional requirements for the EVS and the SVS are based on analysis of RTCA DO-315 [4].

The EVS prototype must perform the following main tasks generic to the existing EVS systems:

- Acquire images from the sensor unit;
- Synchronize the video input of multispectral images with the onboard computer;
- Process and fuse multispectral images for visual enhancement;
- Display the EVS image on Head-Up (HUD) and/or Head Down (HDD) displays.

The SVS prototype basic requirements are:

- Obtain information about coordinates, altitude and orientation of the aircraft;
- Generate 3-D image of a terrain with a model representation of objects (buildings, runways, etc.), and vector graphics flight symbology;
- Display the SVS images on HUD and/or HDD.

Also, the following advanced tasks are a study of the project:

- Detect typical aerodrome objects (e.g. runway, obstacles) on the EVS image;
- Combine the EVS image and the results of automatic detection of typical aerodrome objects, represented in the form of graphic primitives;
- Combine the enhanced image and elements of SVS image.

The following section briefly addresses several fundamentally important principles of the EVS and the SVS development.

## 4 The Main Principles of the EVS/SVS Prototypes Development

### 4.1 Computer Simulation and Its Role in the Development Process

The EVS and the SVS prototypes must operate in an extremely wide range of conditions determined by many factors, all combinations of which are very difficult and economically impractical to attempt to register in real flight experiments. Such factors can include different weather and visibility conditions, different terrains, various airports, different types of runways, finally, various situations due to the presence of obstacles on a runway.

Obviously, all mentioned factors should be simulated and the program of simulation experiments should be extensive enough to ensure reliable EVS and SVS operation in real conditions. The simulation can also be used to explore the range of operating conditions. The quality of simulation should be constantly verified on conformity by the flight experiments data.

Within the R&D project the simulator was developed for imitation of TV and IR sensor outputs and for EVS/SVS/CVS functions testing through the use of computer graphics generated imagery.

The main component of the simulator is an External Data Simulation System (EDSS). The EDSS includes 3D models of terrain and infrastructure, dynamic models of ground objects and provides realistic view of out-the-cabin environment with imitation of weather conditions, time of day, atmosphere conditions, sky textures (Fig. 2).

**Fig. 2. Out-the-cabin View Simulation with Fog**

The considerable amount of video was generated by the EDSS for testing of the EVS, the SVS, and the CVS in different conditions.

### 4.2 A Visual Programming Language Approach for the Algorithms Development

In hardware-software systems such EVS, which includes a number of sensors and other sources of information as well as a number of algorithmic units that should work jointly in synchronous or asynchronous mode, the important role is given to a special software platform that allows consideration of all these parts (hardware and software) as a toolbox of visual components with input and/or output links for data flow.

In this case, the developers are able to easily change the configuration of the system, activate and deactivate various sensors "on the fly" to modify and try out different processing algorithms, quickly generate the necessary reports of algorithms testing.

For these purposes the special integrated image processing environment was developed. It is based on "frame-oriented" programming technology and provides the possibility to form interactively any processing schemes from available blocks (frames) without using programming languages.

Employing of such environment has significantly reduced the development and testing cycle of the EVS and the CVS computer vision algorithms and software.

### 4.3 Multispectral Data Acquisition Using Real Sensors

An important element of the EVS development is a database of multispectral images of objects specific to airport runway area.

A number of ground and flight experiments were performed to create the database which contains multispectral image sequences, sensor characteristics, navigation and flight control data, date and place of registration, and weather conditions. Along with algorithms development, the database was also been used to evaluate informativity of spectral ranges in different weather and time conditions and to select the most appropriate set of sensors for the EVS prototype.

### 4.4 Testing EVS/SVS Interaction with Onboard Systems

Another important task is integration of EVS/SVS/CVS with other sensors and onboard systems. Without solving this task it is impossible to speak about reliability of the systems, because unforeseen errors usually occur exactly at the junction of several information, software and hardware units. Since on the ground position there is no possibility to fully duplicate the operation of all onboard devices, it is necessary to emulate some real devices by using actual records of their signals or corresponding mathematical models.

The EVS/SVS/CVS interaction with other onboard systems is tested at the IMA bench (Fig. 3).

**Fig. 3. IMA Bench with EVS/SVS/CVS Functions**

In addition to the actual onboard equipment the bench includes a flight deck simulator with real controls and aircraft flight simulation system [5]. The bench components use a local network to exchange video sequences, flight and navigation data, and control signals.

## 5 The EVS Algorithms Review

The first generation of the EVS systems, which have passed certification and are available on the market, is mostly a type of “sensor-to-display” systems. It means that the IR imagery is usually displayed directly from a sensor or after some brightness and/or contrast adjustment. A very few systems implement an image fusion (e.g. Max-Viz 600 [6]).

Ongoing research efforts to expand EVS, SVS and CVS capabilities are mainly focused on the improvement of image enhancement algorithms, TV, IR and Millimeter Wave radar data fusion, objects detection from geospatial database (e.g. a runway), real and synthetic images fusion (see for example [7–11]).

To ensure competitiveness of the EVS prototype, the researches ought to be conducted for all mentioned tasks. Up to the date, the original algorithms for image enhancement, TV and IR images fusion, and runway and obstacles detection were developed and are briefly presented in this section.

It is difficult to compare these algorithms with the ones of competitors due to lack of public datasets such as used to test video surveillance or biometric applications (e.g. PETS, ETISEO, CANDELA, YTCelebrity, etc.). Therefore, verification and validation of the algorithms should be based on the extensive experimental work using simulated and real flight data.

A set of ground and flight tests have shown that the developed algorithms are robust enough and provide a real-time data processing using computational resources of the IMA platform.

### 5.1 Image Enhancement

For image enhancement, the modification of Multi-Scale Retinex [12] (MSR-EVS) was developed. The MSR-EVS has the following distinctive features unique to the EVS prototype:

- A new procedure of image smoothing is used to obtain multi-scale brightness estimation in more computationally efficient way as compared to existing techniques.
- A new image normalization procedure is developed for an automatic adjustment of brightness and removing "flicker" effects on result video sequences.

Example of the MSR-EVS image is shown on Fig. 4.

(a)

(b)

**Fig. 4. Example of image enhancement: a) source TV image, b) MSR-EVS image**

## 5.2 Image Fusion

An image fusion algorithm is based on Pytiev's morphological approach [13–15], which provides convenient formal description of multi-spectral images.

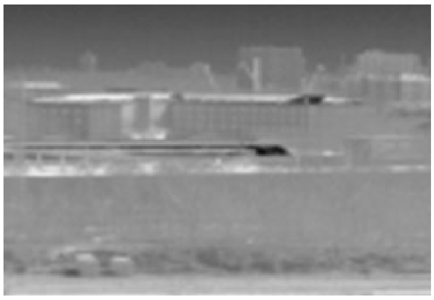
Input data for the algorithm is represented by three geometrically matched grayscale multi-spectral images namely TV, IR1, and IR2.

The main steps of the algorithm are described as follows:

- Obtain the morphological shape (labeling of connected regions) for IR1 image using a histogram-based segmentation. The histogram modes are found by optimization of global separability criterion for $n > 1$ modes.
- Calculate the morphological projections for TV and IR2 images on the shape of IR1.
- Form the fused image by a weighted sum of TV and IR2 morphological projections.

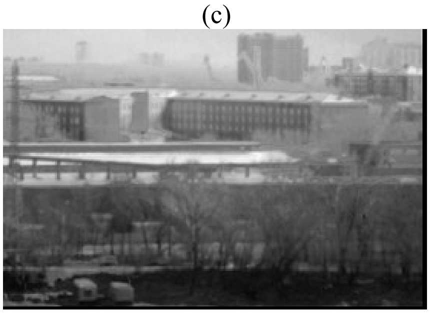
An example of image fusion obtained in ground experiments is shown on Fig. 5.

(a)



(b)

(c)



(d)

**Fig. 5. Example of image fusion: a) MWIR image, b) LWIR image c) TV Image, d) fused image.**

### 5.3 Vision-based Runway Detection

A robust and computationally effective algorithm for automatic detection of a runway on video sequences was developed for the EVS [16]. The algorithm has four main steps:

- The detection of the horizon;
- The detection of the runway longitudinal edges with support of the horizon position;
- The detection of the runway horizontal edges;
- The spatio-temporal filtering of the runway position.

The horizon is detected by using navigation information as an initial approximation along with the image processing procedure based on Hough Transform (HT). The horizon line is assumed to correspond to the local maxima in the HT accumulator such that on the one side there is a free space (sky), and on the other – an informative region (land) (Fig. 6).

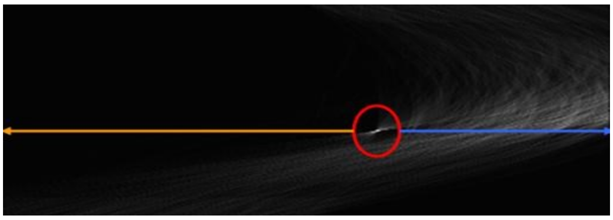


**Fig. 6. Horizon feature on the HT accumulator: local maxima which divides informative region (right) and constant brightness area (left).**

Detection of the runway longitudinal edges is based on the original modification of Hough Transform – Projective Hough Transform (PHT). 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 PHT accumulator is calculated using parametrization ($x_1$, $x_2$), where $x_1$ is the vanishing point of runway boundaries, $x_2$ is the intersection of runway middle line and bottom line of the image (Fig 7). The rotation of runway middle line in the runway plane corresponds to moving the vanishing point along the horizon. The shift of the midline line to the left or to the right in the runway plane corresponds to the shift of $x_2$ along the bottom line of the image.

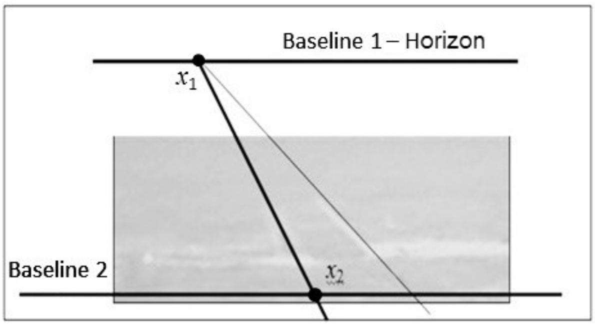
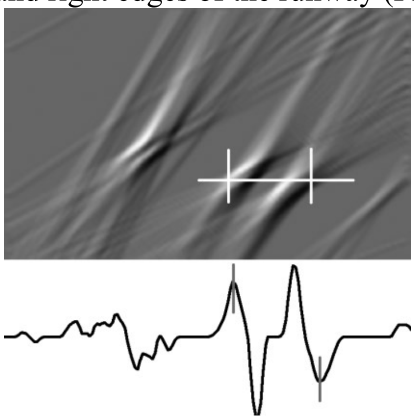



**Fig. 7. Parametrization of the PHT.**

Then the task is reduced to the detection of such a horizontal brightness profile that has symmetrical local extremums of maximal amplitude in the PHT differentiated accumulator. These extremums correspond to the left and right edges of the runway (Fig. 8).



(a)

(b)

**Fig. 8. The detection of runway longitudinal edges: (a) brightness profile of the PHT accumulator with symmetrical local extremums of maximal amplitude, (b) corresponding longitudinal edges.**

To determine the position of the top and 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, taken inside the longitudinal line triangle.

At the final step the spatio-temporal autoregression filtering of the following runway parameters is performed: horizontal image coordinate of vanishing point, distance from the end of the runway to the horizon, distance from the beginning of the runway to the horizon, angle between the vertical line and center line of the runway, angle between left and right boundaries of the runway.

## 5.4 Vision-based Detection of Obstacle on a Runway

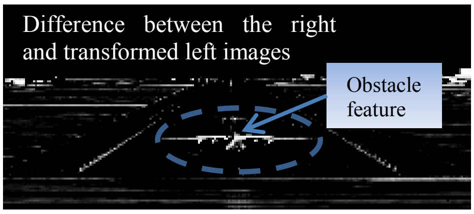
Another innovative feature of the EVS prototype is the algorithm for detection of obstacles on a runway. In the context of this work the “obstacle” means 3D object rising above the runway and making unsafe or impossible to use the runway by approaching aircraft. For example, the obstacle can be an airport service car or another aircraft.

One of the proven approaches to obstacle detection problem is stereo vision [17]. But from the design reasons, the EVS prototype cannot be equipped with a stereo system.

So, the special algorithm was developed, which preserves the benefits of stereo vision but uses onboard monocular video system [18]. The required stereopair is formed as a result of camera movement (“stereo from motion”), where the “left” image of stereopair is the image obtained at time $t_1$ and “right” image obtained at time $t_2$, $t_1 < t_2$.

The main idea of the detection algorithm is as follows. The transformation of the left image to the right image plane is performed using a projective camera model. For runway points, the right and transformed left points are the same, but for obstacle points there is a shift between the corresponding right and transformed left points. This shift leads to an intensity deviation on the difference of the right and transformed left images, which is used as the main obstacle feature (Fig. 9).

(a)

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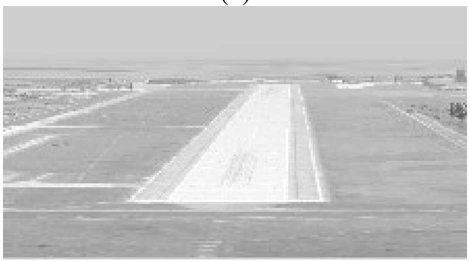

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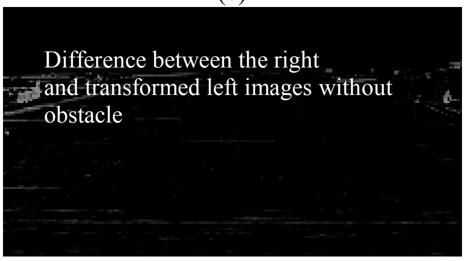



(d)

**Fig. 9. Examples of feature images for obstacle detection: (a) obstacle image, (b) feature image for (a), (c) runway image with no obstacles, (d) feature image for (c).**

Parameters of the left image transformation are found by the method of least squares using two sets of matched runway points detected by the computer vision system.

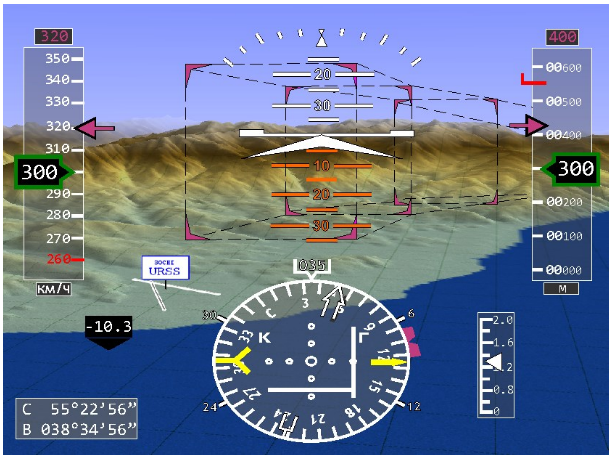
## 6 SVS Function

The prototype of the synthetic vision function provides the real-time 3D rendering of terrain and obstacles (Fig. 10). A natural view of generated 3D image is based on the following innovative approaches [19]:

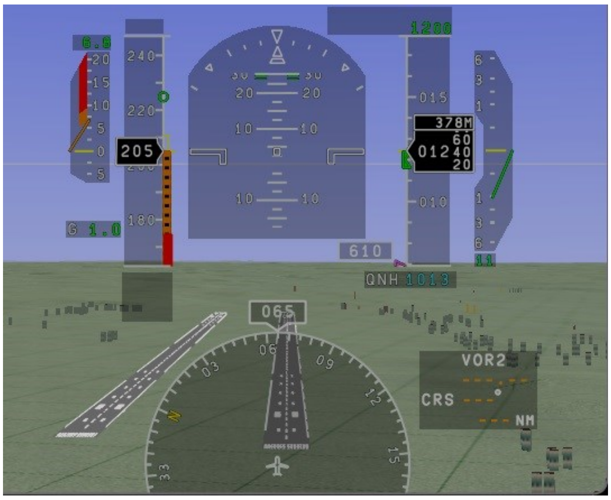
- Both texturing and hypsometric methods are used for 3D rendering of terrain.
- Textured geometric shapes are used for the each type of displayed obstacles.
- Sky image rendering is based on a sphere model with the use of interpolated texture and fog-effect.
- 3D-symbols of navigation objects are included in the SVS image.

The SVS obtains data from terrain, airports, obstacles, and texture databases. The source data can be stored in various formats such as digital elevation model (DEM), Digital Terrain Elevation Data (DTED), SHaPefile (SHP), Keyhole Markup Language (KML), etc., or in Storage and eXchange Format (SXF) used in the Russian Federation. To provide a real-time processing of 3D data, the source data is converted into a special onboard format.

The SVS software uses hardware-supported implementation of OpenGL. A high performance (25–30 Hz) of the SVS image synthesis is ensured by optimization of the onboard databases and implementation of different levels of image details, depending on the distance to viewpoint.




(a)




(b)

**Fig. 10. Examples of the SVS images: (a) mountain landscape, (b) 2D "flat" landscape**

## 7 CVS Function

CVS function combines an image from onboard optical sensor (e.g. EVS infrared camera) with a computer-generated (synthetic) 3D image of the external view and displays the combined image to a pilot.

Since the synthetic image is generated by relying on navigation parameters of an aircraft, which are measured with errors, a problem of sensor and synthetic image matching must be solved at the first stage.

### 7.1 Sensor and Synthetic Image Matching Algorithm

The proposed algorithm is based on the photogrammetric approach. The idea is, firstly, to compensate navigation errors with the use of exterior orientation procedure, and only then to create the 3D image of the external view, which exactly matches to the sensor image.

The exterior orientation requires reference points of known geospatial coordinates. Since the CVS system is applied generally on approach and landing stages, it is convenient to use the reference points from airfield infrastructure objects.

In the current version of the algorithm, the corner points of the runway are used as the main reference points, which are found by the runway detection procedure (see Section 5.3), and marker lights at the start of a runway as additional points, which are found by Harris detector [20].

The synthetic 3D view is generated as follows. An initial position of virtual camera is defined by the navigation parameters of the aircraft. The exterior orientation procedure 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 runway points and the corresponding points on the image. The residuals are computed on the image plane as the distances between the detected runway points and projections of the runway points to the image.

### 7.2 Experimental Results

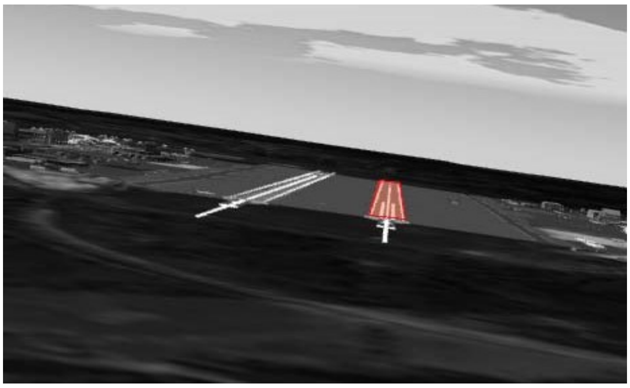
The developed CVS function was tested using the EDSS (see Section 4.1). An aircraft landing at the base glidepath was simulated during the experiments. The CVS function was started within the flight visibility of the runway. The CVS receives a TV image, modeled by the EDSS (Fig. 11 a), the coordinates of the runway points on the TV image (Fig. 11 a), the coordinates of the runway points in the geospatial coordinate system, and the aircraft orientation with simulated errors.

An SVS image (Fig. 11 b) is formed by the SVS function prototype (see Section 6).

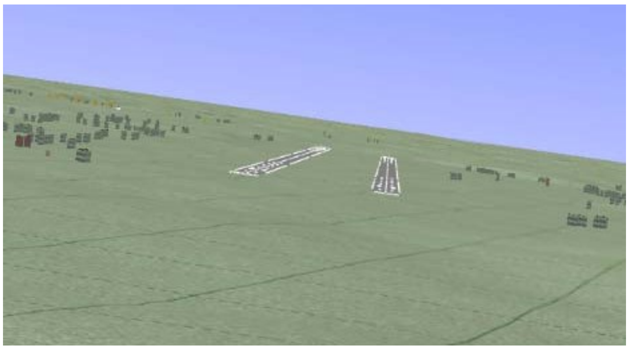
An example of combining TV and SVS images without the exterior orientation, just as simple overlay of images, is shown on fig. 11 c. Result of TV and SVS combination after exterior orientation procedure is shown on fig. 11 d.

The experiments have shown that on a base glidepath the CVS provides image combination with pixel accuracy – even in the case of significant navigation errors.

Further CVS research will be aimed at improving the robustness and accuracy of the CVS algorithm by applying a larger set of reference points in the exterior orientation procedure. These points are assumed to be obtained by the automatic detection and identification of not only the runway but other types of airfield infrastructure objects as well.



(a)



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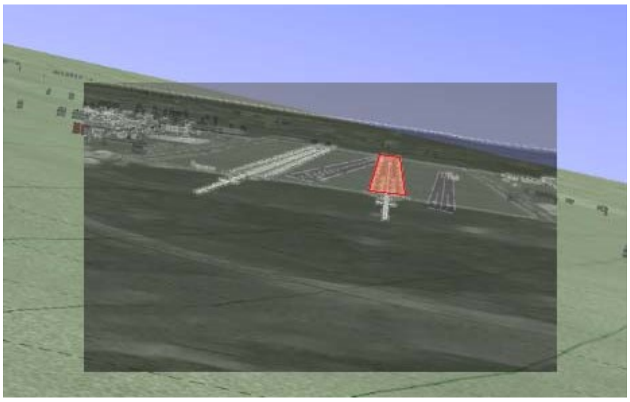

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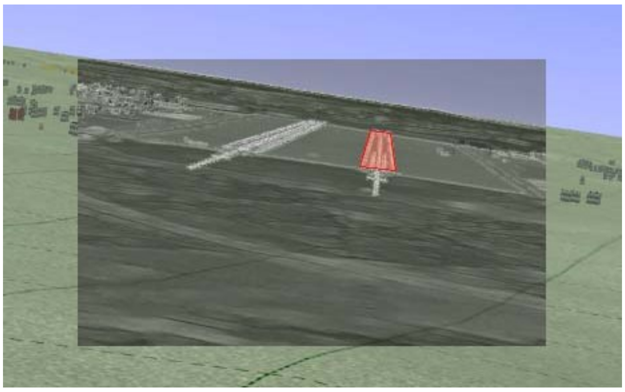

(d)

**Fig. 11. An example of CVS image creation: 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.**

## 8 Conclusions

The paper describes the current results of an R&D project aimed to create the advanced prototypes of EVS and SVS.

The EVS design involves the use of three sensors: TV, SWIR, and LWIR. The computational platform for the EVS and SVS prototypes is based on VPX 3U IMA modules. The algorithmic solutions have been developed for image enhancement, image fusion, vision-based runway and obstacles detection, synthetic and combined vision.

Different hardware and software elements of the EVS and the SVS were tested in flight experiments.

The nearest work plan includes the integration of the EVS optical-electronic unit with the IMA platform, further development of algorithmic solutions, ground and flight tests of the EVS, SVS, and CVS functions.

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