Middle-East Journal of Scientific Research 19 (4): 479-486, 2014
ISSN 1990-9233

DOI: 10.5829/idosi.mejsr.2014.19.4.13693

Combined Correlation-Extremal Navigation System to Identify AV Location by Terrain Relief and Landscape Objects with the Use of the Stereo Photogrammetry Method

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Abstract: How to build correlation-extremal navigation system of flying device in which the location of the aircraft is identified by digital map of the heights with use of additional information about the earth's landscape objects (plants, buildings etc.)? Input data needed for operation of navigation system are formed by technical vision monocular system. System building principles and the stages of data processing in navigation system are considered in detail. The authors consider the issues of how to build hardware and software mock-up of navigation system and perform outdoor tests to evaluate accuracy of identification of aircraft coordinates.

Key words: Stereo photogrammetry · Vision system · Correlation-extremal navigation · Elevation map · Landscape objects map · Hardware and software mock-up

INTRODUCTION

While designing new navigation systems intended for use at aerial vehicles (AV) special attention is paid to invention and updating of intellectual means to guarantee high-accuracy identification of AV in any conditions regardless of hours of the day, weather [1]. Introduction of new requirements to accuracy and reliability of navigation was determined by principally new opportunities discovered in the sphere radio-technical systems, technical vision systems, inertial systems, micromechanics etc.

One of the areas of development of navigation system is the use of geo-physical fields (GPF). AV location is identified through correlation by onboard navigation system (module) of observed GPF with its reference image stored in the computer. While doing correlation the aim is to find maximum of correlation function, that is why such navigation system is called correlation-extremal navigation system (CENS) [2, 3].

Development of CENS started in the USSR and USA in 60-s of XX century. Detailed review of CENS based on GPF can be found in the works [4-6]. In particular, significant results were achieved in the sphere of designing CENS with the use of GPF of Earth's relief (navigation system TERCOM (Terrain Contour Matching) and SITAN (Sandia Inertial Terrain Aided Navigation), optical field (DSMAC, Digital scene matching area correlator), radio-location field (RAC, Radar Area Correlation), MICARD (Microwave Radiometric).

This work contains solution of a task of building a high-accuracy CENS by terrain relief for unmanned AV of different types. Higher accuracy of location identification can be achieved thanks to the use of following:

- Formation of terrain relief is done on the basis of stereo-photogrammetry method with the use of sequential snapshots of terrain obtained by monocular vision system (VS) which operates in optical wavelength range – RGB. Stereobase is formed thanks to the shift of the AV between snapshots;
- Side by side with traditional approach, based on matching of reference and recovered maps of terrain relief we propose to use additional information about the results of searches of maximum correlation function between in-land objects identified on the restored heightmap (DEM, Digital Elevation Model)

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and high-accuracy reference map of landscape objects. In order to build maps of such objects the data on corresponding layers of cartographical information of any modern geo-information system can be used [7].

The idea of 3D-scene reconstruction from stereo images is not new: basic equations of stereo-photogrammetry were published in 70-80s of last century. Great contribution into development of theoretical foundations of stereo-photogrammetry was made by Lobanov A.N., Beloglazov I.N., Kazarin S.N., Faugeras O., Hartley R., Pollefeys M., Zhang Z. and others [8-11]. Detailed descriptions of how to form stereo images are given in works [12-14].

Adaptation of existing and development new approaches and algorithms to solve the problems of restoration of 3-D map of terrain while forming stereo-pair (or stereo-sets) thanks to the motion of camera platform is of special interest. Use of monocular camera in CENS allows to simplify the design greatly, reduce dimensions and costs of navigation system in comparison with binocular VS.

Principle of Operation of CENS: Data processing stages. While providing information and algorithm support of CENS focus was done on solution of the following key problems:

- Identification of VS camera orientation parameters necessary for restoration of terrain relief (the parameters of mutual orientation of two camera positions at the moment of formation of stereo-pair pictures) and for identification of AV location with use of benchmark map of heights (parameters of camera's orientation in regard to Earth at the moment of formation of basic image of the stereo pair);
- Division of unified restored digital elevation map (heightmap) into Digital Terrain Model (DTM) and the map of landscape elements (anthropogenic objects, green zones etc.) in order to realize independent schemes of data processing;
- Correlation of reference and restored heightmaps and maps of objects when ratio of scales and orientations of these maps are unknown;
- Selection of proper method that can be used for combining information about location of AV obtained by 2 independent algorithms of correlation.

The order of data processing is demonstrated in Figure 1.

At the first stage independent pre-processing of every image of stereo-pair is done in order to improve characteristics of picture which will facilitate search of matching points while restoring the heightmap. While developing algorithms of distortion correction we used the model of distortion with axial symmetry and radiant components which is the most common case of distortion of standard non-metrical systems. Smoothing of local sharpness in order to increase detailization of too dark sports (too light spots) is done with the use of Wallis filter [15]. In the same time after the Wallis filter subsequent global normalization of picture is necessary in regard to dynamic range of brightness levels. Otherwise significant difference in brightness of appropriate points in stereo-pair pictures will influence accuracy of restored heightmap done by stereo images.

Second stage is intended for identification of mutual orientation of stereo-pair pictures and compensation for changing orientation angles and the shift of pictures along one of the axis. Solution of this task is connected with preliminary finding out in the pictures of the zones which correspond to changes of background texture. Such zones are the most “suitable” for searches of matching points in the stereo-pair. Identification of characteristic points (with the aid of Harris detector) allows to increase accuracy and make algorithms of processing snap-shots at the next stages not so time-consuming [16].

The task of identification of angles of mutual orientation and images shift is a classical stereo-photogrammetry problem [8, 14]. Since stereo-photogrammetry equations are non-linear, the simultaneous equations are usually solved by approximation method, with this purpose the equations are transformed into linear form and then the solution is found using least squares method [17, 18].

Calculated parameters of mutual orientation of stereo-pair pictures are used for transforming images to a form in which changes of orientation angles are compensated – between the moments of shooting stereo-pair pictures and moving takes place along only one of the axis as if the camera was fixed at a moving platform with one degree of freedom. Such transformation allows to reduce complexity of algorithms needed to build disparity map because the search for matching point is limited to 1-dimention problem.

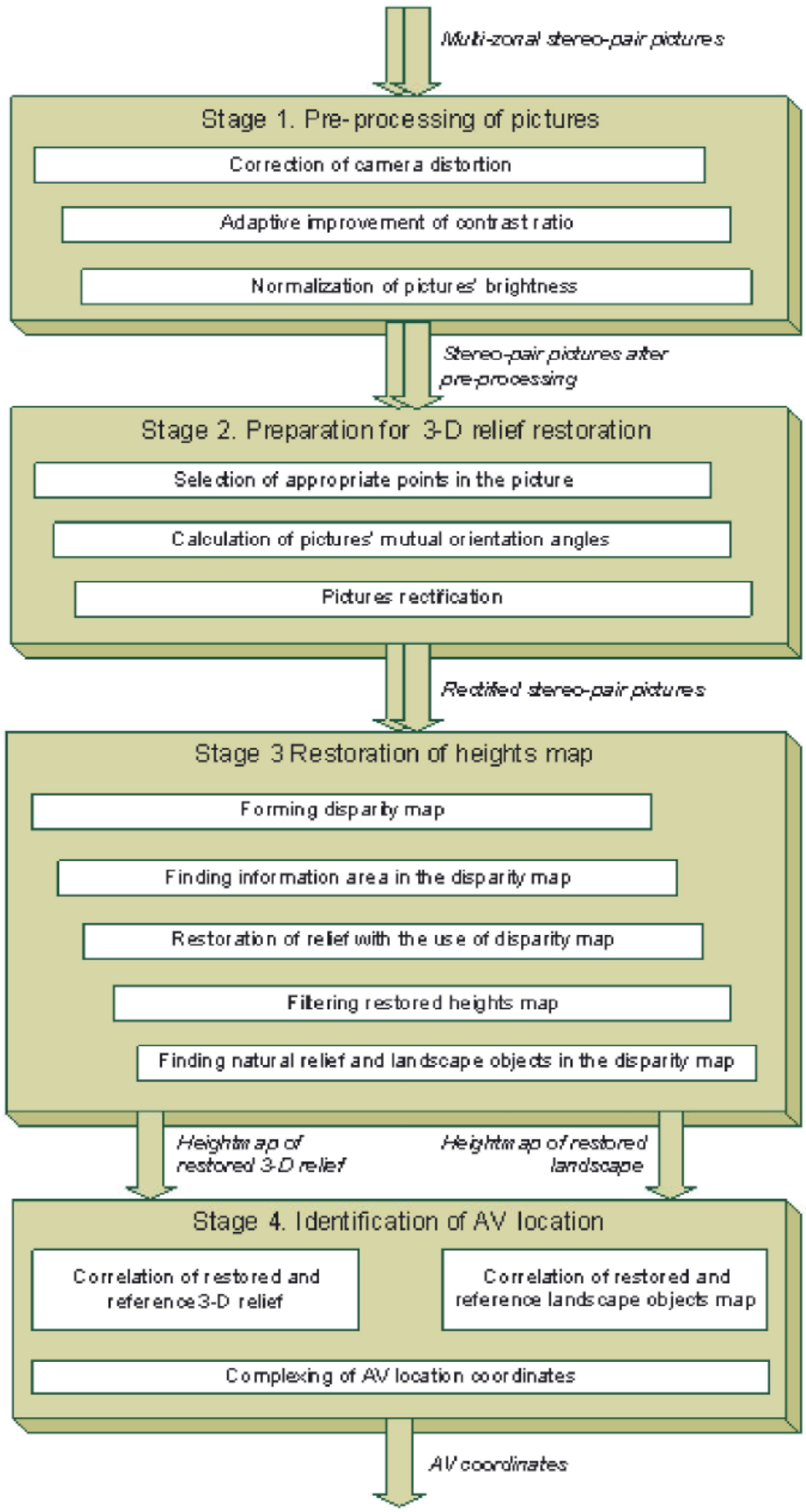


Fig. 1: Data processing stages in CENS

That is why the algorithm of rectification of snapshots consists of 2 stages:

- Projection of the second image on the plane of 1st one;
- Flat turn of both images to compensate the shift.

Third stage is characterized by restoration of height (DEM) and formation of the 3-D relief map of the terrain (Digital Terrain Model, DTM) and the map of landscape objects.

Detailed investigations and comparative analysis of different algorithms of building the map of disparity can be found in the works [19-21]. Preliminary analysis and experiments led to conclusion that SGM algorithm must be used for building CENS which is based on the idea of finding correlation by calculation of "weight" of every possible matching point through the difference in intensivity of potentially matching pixels and using "penalties" if signs of incorrect match are available.

Formed by SGM-algorithm map of disparity contains non-informative zones which appear because of unfilled regions on the smoothed stereo-pair pictures which SGM algorithm perceives as informational. To solve this problem is possible if to cut the map of disparity in correspondence with boundaries of informational regions of stereo-pair pictures.

While restoring heightmap (DEM) with the use of disparity map a set of vectors is formed describing 3-D coordinates of the earth surface points in the world coordinates system. The values of obtained coordinates are standardized in regard to given size of stereo-base. In order to obtain absolute values of point's coordinates it is necessary to get additional information about accurate value of stereo-base.

Restored heightmap can contain mistakenly restored points because of inaccuracy of the disparity map or impossibility to match some points on stereo-pair pictures. In order to get rid of these points restored map DEM is filtered by points' height.

In order to catch landscape objects an algorithm was developed which is based on identification of geometrical primitives on the heights map with the use of Haf-transformation [22].

Figure 2 shows an example of heights map formed at this stage.

Fourth stage - matching of benchmark and restored maps. Original (benchmark) maps of 3-D relief with necessary resolution can be built on the base of available topographic material (this approach was used while testing CENS). In order to form benchmark maps of landscape objects snapshots made from an aircraft can be used, cartographic data, results of geodesic measurements. The maps of earth landscape objects (benchmark and restored) can be presented in binary form and disregard the heights of objects. This simplifies finding maximum of correlation function greatly.

Main problem while matching restored and benchmark maps are unknown ratio of the scales and mutual orientation of benchmark and restored data. Restored map of heights DEM (and, therefore, the map of 3D relief and the map of landscape objects) can be sloped at some angle in regard to horizontal plane because of the shooting at this angle in regard to vertical axis in world system of coordinates. To get rid of this slope at the stage of restoration of relief is possible in two ways: either knowing apriori the angles of external orientation of camera at the moment of shooting of every snapshot (for example, thanks to use of precision module of identification of AV orientation angles) or using similar apriori known land mile-stones.

In the framework of CENS in order to solve this task we used the method based on SIFT (Scale-Invariant Feature Transform) algorithm [23].

Experiments have shown that approximate values of mutual orientation parameters and the scale must be identified first with the use of binary maps of landscape objects because they need less work. Only after that, having limited the range of possible values of needed parameters the algorithm of identification of mutual orientation and the scale on the 3D-relief maps is used.

AV's coordinates obtained with the use of 2 matching algorithms (by relief and on-land objects) are combined and delivered as the results of operation of CENS.

CENS Hardware and Software Mock-Up and Performing Tests: In order to check functionality and efficiency of proposed CENS structure we developed CENS hardware and software mock-up which includes 2 parts: on-board (installed in AV) part and on-land part.

On-board part of the mock-up is intended for formation and accumulation of snapshots with the use of multi-zone video-camera with high spatial resolution (at this stage we used RGB-camera with spatial resolution of 16 mega pixels and for doing extra-trajectory measurements during the AV flight. Generalized scheme of onboard part of the mock-up is demonstrated in Figure 3.

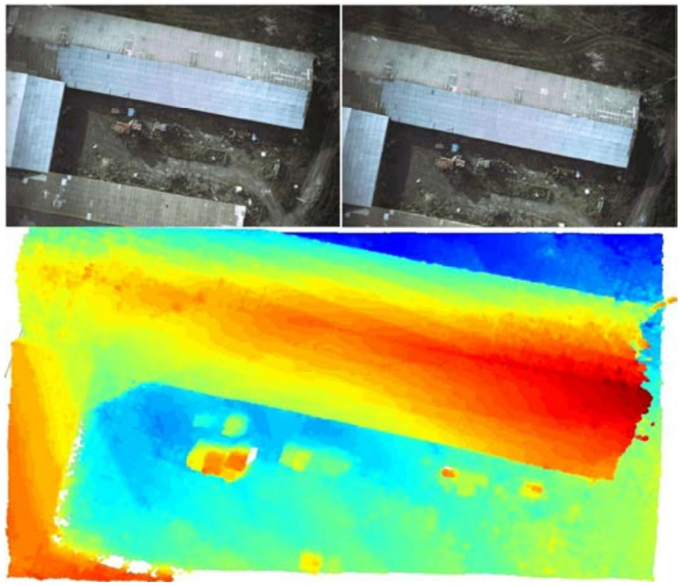


Fig. 2: Results obtained with the use of stereo snapshots processing and heights map restoration algorithm by multi-zonal stereoscopic pictures. Above - original stereo-pair picture; below - restored heights map (colour shows relative height of pixels: blue colour - minimum height, red - maximum height)

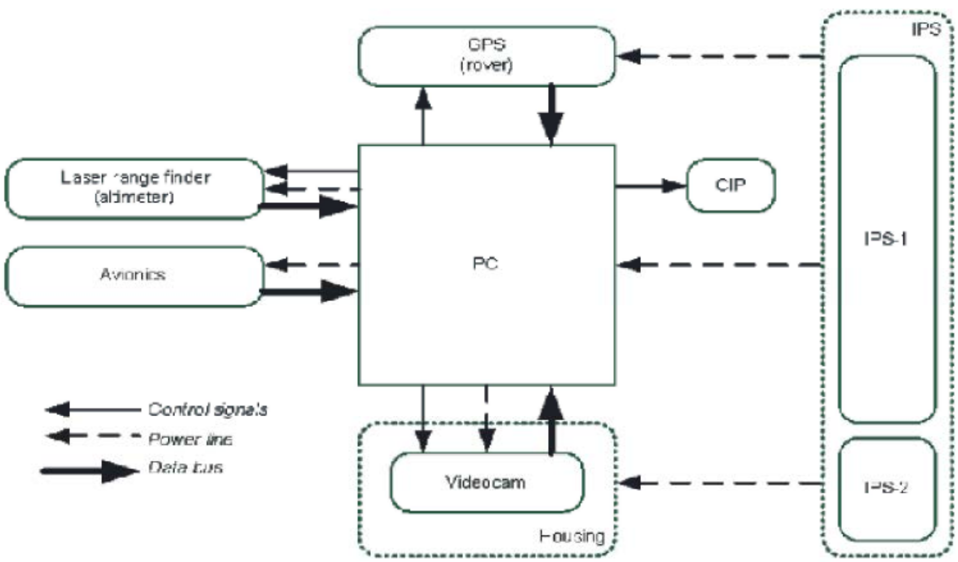


Fig. 3: Generalized scheme of interaction of onboard part units of CENS mock-up

Computer module of onboard part is a PC with high-speed (not less than 45 Mega bite per second) and vibration-resistant storage subsystem which is formed solid-state drives connected into one RAID-massive [24].

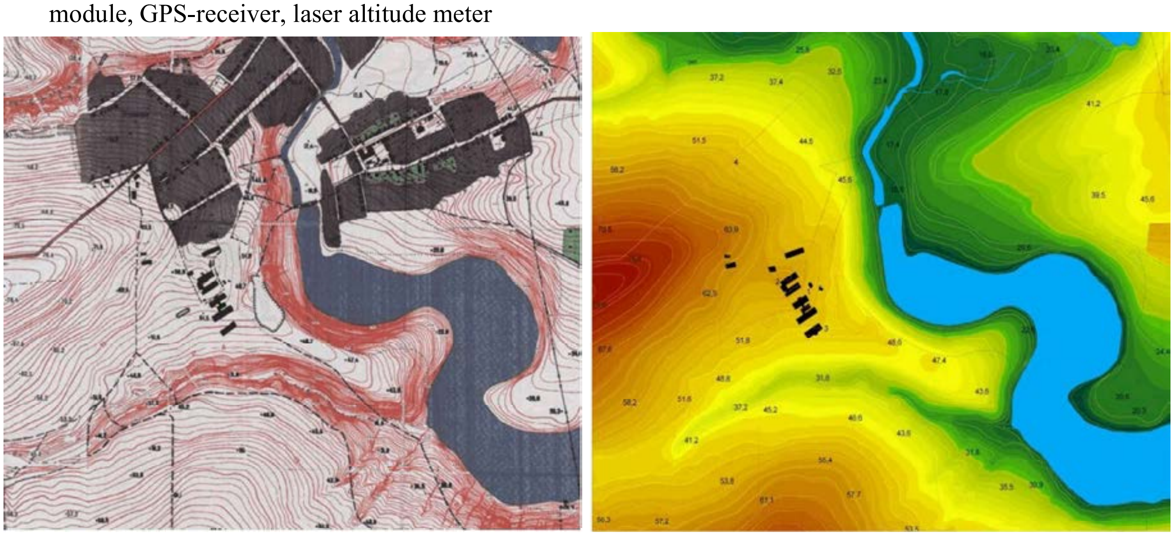
Computer module is connected to video-camera (which is inside of housing) and navigation devices to make test measurements in order to evaluate accuracy of CENS' results (Figure 4). Control and indicators panel (CIP) is intended for monitoring and control of the mock-up by the pilot in flight.

Data formed in the onboard part after flight completion will be passed over to on-land mock-up part in order to control, checkup, process and evaluation of the preciseness of identification of AV location.

On-land part of CENS' mock-up is a computer program which is installed on PC of standard configuration. Program is written in C# language with the use of the platform Microsoft. NET [25-27].

In order to perform tests we chose a plot of land which is characterized by alternating relief and availability

Fig. 4: Equipment of hard-soft CENS mock-up. Main equipment: computer module, video-cam in protective shell. Additional equipment for extra-trajectory measurements and evaluation of relief restoration accuracy: avionics module, GPS-receiver, laser altitude meter



(a) (b)

Fig. 5: Fragment of original topographic map of the terrain (a) and built on its base reference 3-D map of the terrain relief (b) with landscape objects (buildings) projected on it. Pictures are given in reduced size

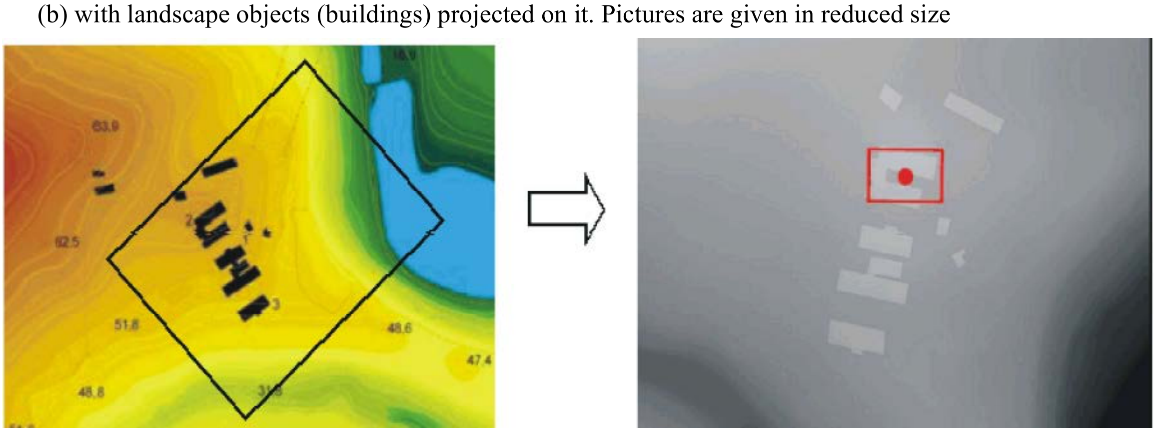


Fig. 6: Illustration of CENS operation's results: location (position) of basic stereo-pair picture in relation to 3-D relief benchmark map (on the left); location of FD identified by CENS (on the right)

of buildings. On the base of available geographic map of low preciseness (Scale 1: 100 000) and after additional geodesic works intended for measuring of coordinates of reference points with the use of one of the geo-informational systems, benchmark digital map of relief in 3-D was generated (scale 1:100) (Figure 5). Reverence map of landscape objects was developed in "manual" mode and contained description of buildings as a set of geometrical primitive figures (they are shown in Figure 5 as black rectangular boxes).

Testing CENS mock-up included full cycle of obtaining and processing of data and evaluation of error of calculated by CENS coordinates of location, flight height and orientation parameters of AV by indications of extra trajectory instruments. In order to perform tests hardware and software CENS mock-up was installed in small flying device SP-30 [28].

Figure 6 demonstrates a fragment of reference 3-D relief and corresponding to it fragment of restored 3-D relief with marked landscapes objects. Rectangular shown in the right picture corresponds to the orientation of VS-camera, red point - to the location of AV calculated by CENS.

CONCLUSION

The experiments proved operational functions and usefulness of proposed CENS structure. Use of colour optical snapshots for search of matching points on the stereo-pictures and restoration of heights map allows to increase the preciseness of relief restoration and reduce the number of artifacts in the re-constructed 3-D model in comparison with use of one-channel TVS.

Main factors which influence the preciseness of AV navigation by relief are the particularities of relief and on-land landscape, optical parameters of technical vision system (VS), distance of stereo-base and the degree of reliability of reference topo-geodesic map.

Preciseness of identification of AV's location depending on the height of the flight and the character of the relief, as it was found by experiments, was 8-15 m. The highest precision in relief restoration was achieved at the segments of natural landscape which contained big objects with sharp contours (for example, ravines or buildings). On the contrary, the availability of even smoothed landscape results in less precision of the search for matching points on the stereo-pair pictures and consequently it will be more difficult to identify location of AV by reference heights map.

Inference. Main factors which influence CENS precision are errors in identification of AV orientation parameters. If it is possible to define on the board of AV the speed of flight and the angles of spatial orientation some steps in data processing (for example, identification of stereo-pair pictures' mutual orientation parameters, identification of mutual orientation and the scale of reference and restored maps) can be skipped and received from onboard sensors measurements can be used directly in picture rectification and maps' correlation algorithms.

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