Prompt Terrain Modelling for Navigation, Control and High-Precision Guidance by Aerospace Images

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Abstract: The system has been developed for prompt computation and on-the-fly visualization of terrain models from aerospace photography data for purposes of navigation and moving objects guidance. Visualization is performed on basis of terrain model composed of detailed digital elevation model with orthophoto overlay; texture and quality of thus rendered images comply with that of photography source data, and the model computation can be performed automatically as well. The model applies for navigation and guidance tasks as follows: a) computer reproduction of an actual traversed path; b) route choice and guidance of a moving object using the visualized terrain model and the moving object simulator; c) navigation and guidance of a moving object by comparison of on-board terrain model calculated during the flight to the predetermined one.

Keywords: navigation, control, guidance, aerial photography, visualization

1. INTRODUCTION

The laboratory for Moving Objects Control Dataware by Institute of Control Sciences, Russian Academy of Sciences, has developed a system for prompt computation and visualization of terrain models from aerospace photography data. The system has control interface responsible for camera model movement with features of recording track data and repassing the route.

Visualization is performed on basis of terrain model composed of detailed digital elevation model (DEM) with orthophoto overlay (Alchinov et al., 2006); texture and quality of thus rendered images comply with that of photography source data. The application stores data in specific hierarchical structures providing quick access that ensures rendering rate of tens frames per second.

Computation and visualization area for terrain model can be nearly unlimited. In case source data contain any georeference to some particular Earth-bound coordinate system (i.e. global navigation satellite system coordinates of projection centers or terrain control points), all the data can be output in this coordinate system, otherwise processing is performed in a local coordinate system.

The system has advanced facilities for prompt computation of surface geometry and photoplans enabling relatively fast access to these data for visualization according to source images.

Processing can be performed both manually and automatically. The system comprises many innovative solutions, some of them are patented in the Russian Federation.

Calculated terrain model including DEM, orthophoto and general terrain rendering from different points can be used for navigation and guidance of moving vehicles, in automatic process mode as well. The system developed can find practical application in following particular cases:

1) A vehicle while moving can record its trajectory using global navigation satellite system receiver and other on-board means for determining absolute coordinates. Saved route can be later visualized with the help of computer.
2) The system can be coupled with a simulator of some particular flying or moving object. Using such a frame an operator can (subject to other additional general requirements) choose an optimal route for machine movement over the given terrain model, allowing, for example, high precision access to a prescribed point. This route can be saved, and then its coordinates and other parameters can be used when actually moving along the route in order to accomplish control and guidance tasks, in automatic mode as well.
3) Given sufficient computational facilities, terrain model can be calculated immediately at the time of movement according to the data of on-board photography. Comparing this model with the predetermined one, navigation and guidance technologies can be developed. It will be noted that such navigation and guidance technologies can be the only available option for a machine, failing possibility of using wireless beacons, global navigation satellite system, astroorientation system or other conventional technologies.

2. DATA STRUCTURE OF TERRAIN MODEL AND TECHNOLOGY OF ITS VISUALIZATION

The basic principle is splitting the entire data range into levels with different detail of information representation.

The elements of visible surface appearing further from screen plane comparing to those that are closer are visualized in less detail and are chosen from upper, coarser levels of data representation.

The special format has been developed for level-storing of regular structure for spatial data with nearly unlimited size, which supports quick access to data of each level by rectangles and possibility of storing data for an area of an arbitrary shape.

Such data can be both regular DEM and raster data (orthophoto). There can be any quantity of levels, it depends only on the volume of the information to be processed – the more the volume is the more levels it requires.

One level of regular DEM in this format can be represented as an infinite grid with given spacing between neighboring vertices in X and Y-direction, an altitude mark can be specified for a vertex or indication that the altitude is not specified.

The upper level resolution is four times less than that of the lower level, providing relatively high visualization rate combined with acceptable image accuracy, see Fig. 2.1 and Fig. 2.2.

Levels are stored in files, point altitudes are stored by blocks. The format also provides for storage of interlevel deflections that are used in determining borders of triangle visualization zones.

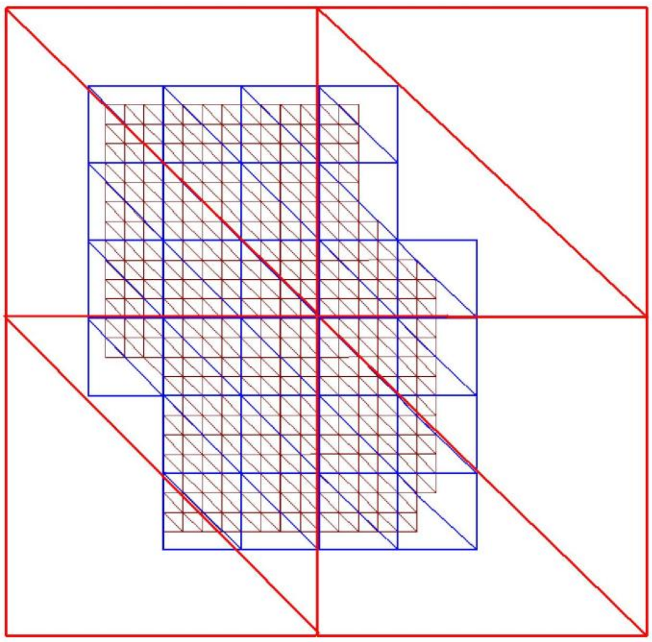

Fig. 2.1. Grid of regular DEM with levels and natural triangulation

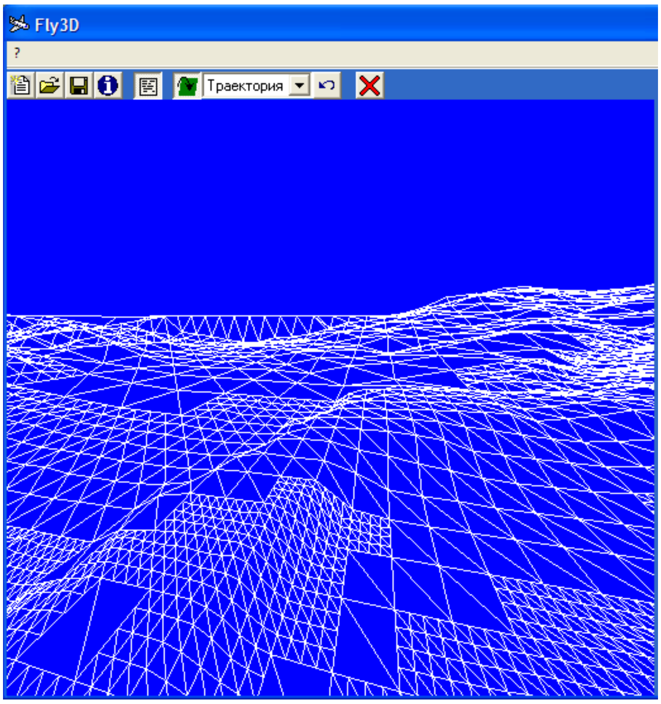

Fig. 2.2. Visualization of terrain model without textures.

A similar algorithm is also developed for terrain visualization in the form of triangle irregular network (TIN). Delone triangulation is used in this case. In the process, triangulations of levels are constructed coherent, i.e. all upper level vertices are also included into any lower level, and there are no edges on the lower level cutting across the upper ones ‘criss-cross’ (Fig. 2.3). The basic principle of construction of vertices of the upper level is calculation of triangles inside which deviation of vertices of the previous level from the triangle’s plane is small. If deviation in a certain point exceeds a certain threshold, then the point is appended to the level and the triangulations of this and lower levels are reconstructed. Construction of coherent levels of Delone triangulation calls for adding an appreciable quantity of points on lower level.

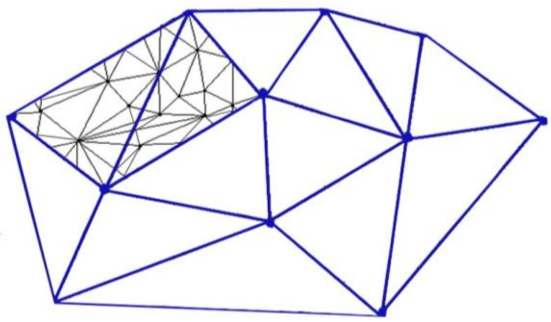

Fig. 2.3. Coherent levels of Delone triangulation (2 meshes)

For flat ground TIN appears to be resource saving, but for mountain terrain such representation does not decrease quantity of triangles significantly comparing to regular DEM. Taking into account constant growth of storage capacity of modern digital storage devices, regular DEM has been chosen for simplicity of implementation.

For storing each raster with photoplan texture standard TILED TIFF and TIFF JPEG formats are used. These tiled formats with image pyramid have been chosen as the most space saving and allowing internal leveled data storage. Texture information, at least at lower levels, is stored in several contiguous files that are structured on the principle of splitting entire area into squares. And of course there is conformity in pixel size and direction of rows and columns with DEM spacing and DEM rows and columns direction (in case of regular DEM).

Data pre-computation for preview is run once at project initialization and comprises image pyramids calculation and raster redrawing, concordant enveloping of higher levels and calculation of DEM interlevel deflections. When visualized the entire relief surface is divided into several zones depending on proximity to the observer. During image page filling, i.e. processing the set of displayable triangles and textures, tasks of determining borders of the displayed zones and combination of triangles on the borders of the zones are solved. Elements of displayed page are taken from buffers which are filled according to the information storage level. Because of buffering, the image page refreshes insignificantly in case of small shifts in the observer's position, and that allows fast data swapping.

One can control camera spatial orientation and view angle, move in desired direction using mouse and keyboard. Flight route can be saved, edited and used for demonstration of flight along trajectory.

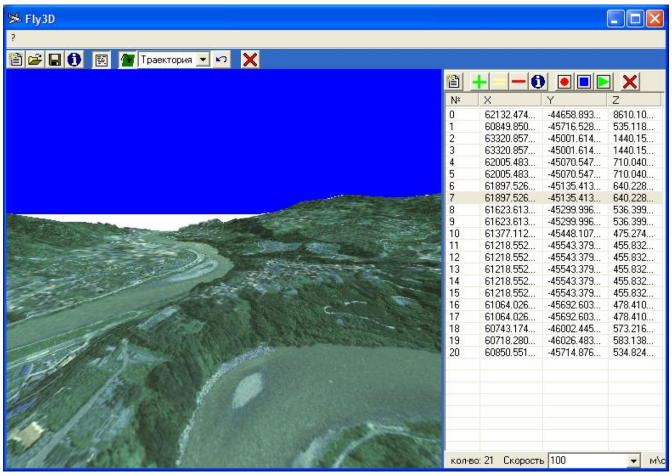

Fig. 2.4. Visualization of terrain model: flight along trajectory

3. PROMPT TERRAIN MODELLING ACCORDING TO AERIAL AND SATELLITE IMAGES

Terrain model computation by photograph data consists of several stages. Actual processing can be performed in different ways and consider additional terrain data, complexity of optical photographing systems, curvature of terrestrial surface, atmosphere refraction etc., therefore we will consider the most widespread technology (Alchinov et al., 2007) in general, see Fig. 3.1.

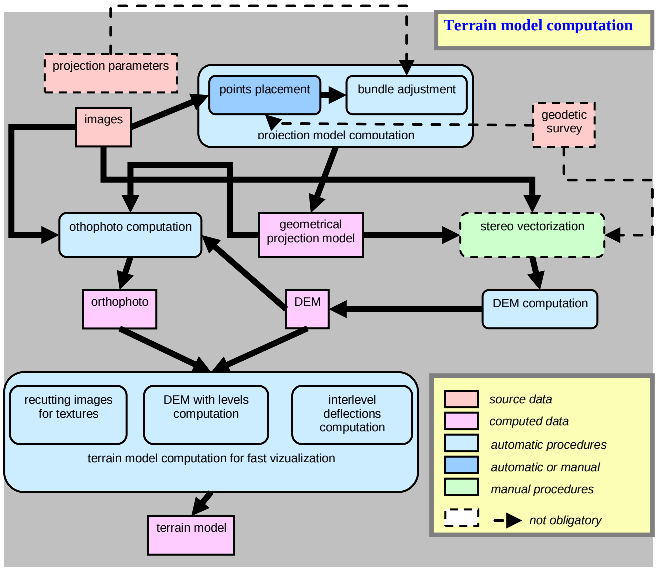

Fig. 3.1. Terrain model computing diagram

At the first stage full geometrical projection model is calculated. It means that for each image position and orientation of the camera and position of the image at the moment of photographing are determined. This process is called calculation of exterior image orientation or bundle adjustment. It gives the possibility to determine for any image point a beam of its probable preimages in space. There is a possibility to use «scanned» space images which sometimes are delivered along with ready exterior orientation.

For calculation of exterior orientation of images operators find in different photos and specify points being images of the same point of terrain. It is necessary to specify several such points for each image. The application can find and place these points on 'legible places' automatically as well, using the algorithms calculating correlation of local images. Then the application constructs the optimal projection model corresponding to minimum distances between the beams of the points' preimages.

When geometrical model is computed, one can proceed to DEM. It will be noted that automatic procedures provide DEM conforming to the surface along with all the elevations, i.e. buildings, trees, grass, etc., while computation of DEM conforming to the proper Earth surface requires 'manual processing'.

The standard 'manual' technology is as follows. Stereo pairs are formed according to photos. Looking at these stereo images, operators extract features of the relief - points and contours in precisely discernible or typical places of relief – along roads, at hill tops, on bases of buildings etc. Since the projection model is known, the application determines three-dimensional coordinates of these objects in space. Using relief objects, the application calculates TIN and then regular DEM. There are also facilities of automatic DEM computation using correlation of images. And one can 'help' the application having specified some relief objects manually in difficult places, especially in woody gullies and ravines, which considerably improves quality of automatically calculated DEM. And fully-automatic relief drawing has proved effective on areas without high vegetation and buildings. The algorithm allows to distinguish low-informative areas such as that covered with water, snow and flat sand, and exclude them from relief extraction. On such areas signal/noise ratio is low and this can result in ‘spikes’ or misidentifications of the surface (construction of relief in detail will be discussed in the following part). It will be noted that if georeference is lacking, all calculations are performed in local coordinates. One may change georeference and projection model at any moment, and then TIN will be automatically calculated by the relief objects determined earlier.

Using DEM, images and projection model, the application draws orthophoto, i.e. the image of terrain corresponding to the specified map projection (each point is viewed ‘directly from above’). Areas are determined on the images that will be used for orthophoto calculation. These areas can be also specified or touched up manually.

In order to determine which pixel of an image corresponds to a given pixel of an orthophoto, DEM in the form of TIN is applied. In case of regular DEM, natural triangulation is used when every mesh is divided by diagonal in two triangles. Every TIN vertex is uniquely mapped into 2D coordinates of map projection as well as into raster coordinates of image according to projection model. Raster coordinates of orthophoto uniquely correspond to 2D coordinates of map projection. Thus, mapping ‘pixel of orthophoto → pixel of image’ is established for pixels corresponding to TIN vertices (Fig. 3.2). For other pixels linear interpolation inside triangles of TIN is used. Piecewise-linear correction transformation, correcting for common points of images, can be also applied in calculation, and other transformations as well.

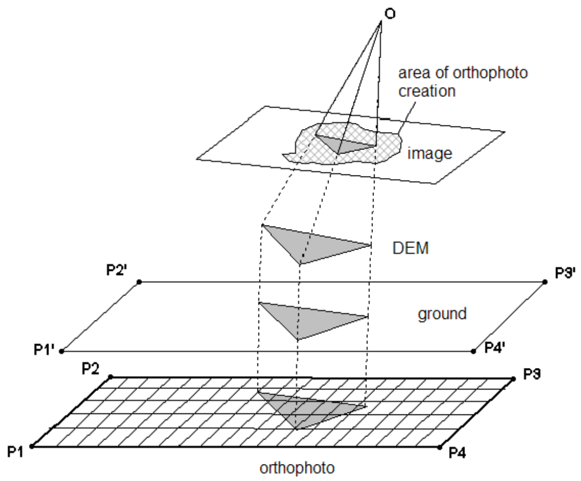

Fig. 3.2. Orthophoto creation: mapping ‘pixel of orthophoto → pixel of image’

The application has all the facilities to obtain high-quality orthophoto: contrast and brightness adjustment (both local and global), interpixel interpolation, etc. An original approach of local brightness adjustment should be mentioned that enables to remove brightness jumps at the boundary of adjacent areas of different images. It solves boundary value problem by means of difference scheme in order to calculate correction for brightness levels of adjacent areas of two images. Corrections calculated in such a way satisfy the principle of maximum, i.e. take their most value at the boundary of an area. This makes it possible to achieve good result, practically always without information loss in image.

System efficiency can be understood from the following example: automatic computation of complete terrain model, i.e. DEM with orthophoto for the area of 100 sq. km (100 aerial photographs scaled 1:10000) with accuracy that is substantially better than one meter takes some tens hours on an ordinary personal computer. The system is also suitable for processing much greater projects, it provides parallel computing on several computers and is proof against input data and operators’ errors. That is, if an error at any previous step is found out during the work, then its correction will not require repetition of routine ‘manual’ jobs at the steps that have been already completed.

4. AUTOMATIC DEM COMPUTATION

DEM computation can be performed in a user defined region (region of interest) on basis of a previously calculated projection model. At first stereo pairs covering the region of interest are determined.

For each stereo pair, regions on images are determined that lie inside the region of interest and where DEM has not been calculated yet. On the left image of the stereo pair on that regions points are placed (by regular grid or in singularities) with density depending on detail of DEM. For these points the application recognizes corresponding points on the right image of the stereo pair, and calculates points with 3D coordinates by determined point pairs using the projection model. Recognition of the corresponding point on the other image of the stereo pair conforms to determination of disparity of the stereo pair in the given point.

Regular DEM comes out as result of interpolation over irregular DEM computed as described above. Relief objects specified by an operator are used in determining of estimates of corresponding points, and for control and correction of calculation results.

Calculation of disparity is a fundamental problem of image processing. There are many methods of such calculation (e.g. classical approach that is by maximum of correlation function). Let’s consider some procedures used in the application that have proved effective.

One approach is based on superposition of preresolved image details of the left and right images. Images are processed by means of convolution of the image’s brightness array with the mask ‘Laplacian of Gaussian’ $\Delta\ g_\sigma$, where Δ is Laplace operator and $g_\sigma(x, y) = \exp(-(x^2 + y^2) / (2\sigma^2))$. Zero level lines of the convolution correspond to objects’ contours resolved ‘to within detail less then σ ’.

Let $f_1(\mathbf{x})$ and $f_2(\mathbf{x})$ be given brightness arrays of the left and right images, $\mathbf{x} = (x, y)$ be an image point. Let $u_1 = f_1 * (\Delta g_\sigma)$, $u_2 = f_2 * (\Delta g_\sigma)$, asterisk to denote convolution. We take as estimate of average shift of the right image relative to the left one the value of $\mathbf{h}$, maximizing the correlation function of the processed images:

$$w(\mathbf{h}) = \int_{-\infty}^{+\infty} u_1(\mathbf{x})\, u_2(\mathbf{x} + \mathbf{h})\, d\mathbf{x} \rightarrow max$$

Function $w(\mathbf{h})$ has more strongly pronounced maximum as against the classical correlation function

$$c(\mathbf{h}) = \int_{-\infty}^{+\infty} f_1(\mathbf{x}) f_2(\mathbf{x} + \mathbf{h})\, d\mathbf{x}$$


Fig. 4.1

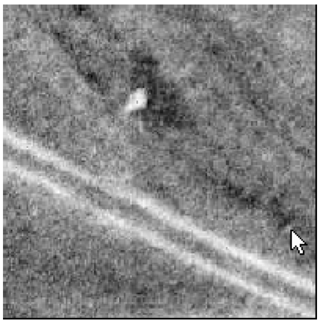
Fig. 4.2

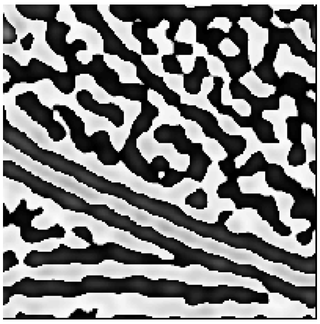
Fig. 4.3

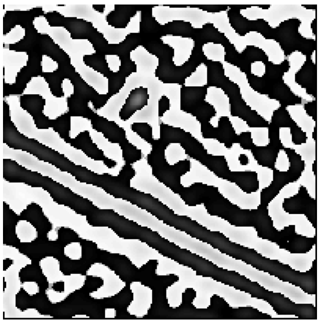
Fig. 4.4

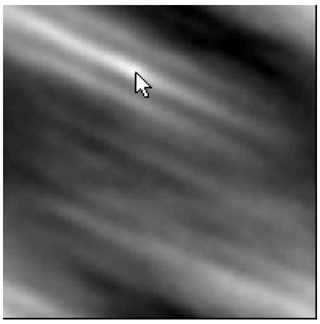
Fig. 4.5

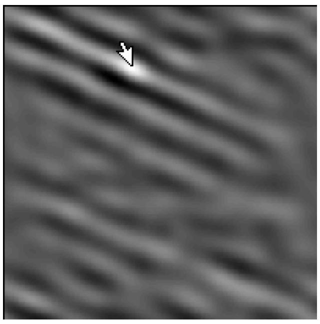
Fig. 4.6

In Figs. 4.1 and 4.2 there is an example of a stereo pair. In Figs. 4.3 and 4.4 there are corresponding processed images u_1 and u_2. Negative values are indicated with darker colors, positive ones with lighter colors. Correlation functions c and w are shown in figures 4.5 and 4.6 respectively. An arrow in Fig. 4.1 points to the center of the image, and in Fig. 4.2 its point is shifted from the center by the calculated disparity vector $\mathbf{h}$.

For computation of $w(\mathbf{h})$ frequency domain approach is used (Calway et al., 1992). Let $F[f]$ be bivariate Fourier transform. Then Fourier transform $w(\mathbf{h})$ is calculated by Fourier transforms of images as follows (# is for complex conjugation):

$$F[w](\boldsymbol{\omega}) = (2\pi)\, \sigma^4\, |\boldsymbol{\omega}|^4\, (g_{1/\sigma}(\boldsymbol{\omega}))^2\, (F[f_1](\boldsymbol{\omega}))^{\#}\, F[f_2](\boldsymbol{\omega})$$

Then $w(\mathbf{h})$ itself is calculated via inverse Fourier transform, and a point is determined in which maximum is taken. Numerical implementation of this procedure based on fast discrete Fourier transform requires on the order of $O(N^2 logN)$ operations (under the assumption that the image size is $N\times N$).

In order to achieve acceptable speed and accuracy while processing large images, pyramid is used. Point search consists of several iterations of the same type. Intermediate images are always square of side $M = 2^m$, they result from a certain rectangle of the source image by the instrumentality of sub-sampling. The center of the rectangle on the left image is chosen in a given point, and on the right image it is chosen in the point resulted from the previous iteration (the initial estimate is chosen from common considerations). The mask parameter σ and the size M keep fixed during iterating. Values $32 \le M \le 256$ provide good results, whereas the stereo pair's source image size can amount to tens thousand pixels.

Separating of spurious and low-information image patches, noise, that can cause errors of false identification of ground surface, is an important issue. In the application an original approach is used that enables automatic recognition of such patches. It only draws on the assumption of absence of discontinuities in visible surface and practically doesn't call for parameters' adjustment. We will describe this approach in short below.

We will refer to points in which disparity should be calculated as primary. Primary points are placed in the working area on the left image of the stereo pair with certain spacing depending on DEM, over regular grid (possibly shifted to the sharpest contour in the neighborhood). Thus, every non-boundary primary point has 8 adjacent primary points, viz. in horizontal, vertical and diagonal directions. For every direction, primary points are grouped into chains of primary points neighboring along the direction. Subsidiary points are placed with spacing of several pixels on every segment joining adjacent pairs of primary points of the chain. In this way chains are formed of primary and subsidiary points. The disparity is determined for each chain in its central primary point according to pyramid procedure, and then run is carried out along the chain to its ends. For calculating the tentative value of disparity during the run, the tentative value of disparity in the previous point is taken as an estimate. Finally, for each primary point there come out four (generally, different) tentative points. If the greatest difference of these four values is less than a certain threshold, then their average value is taken as the value of disparity, otherwise the point is marked as a spurious one.

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