*Digital Fictitious Data for Automatic Mapping Research**

J. D. NEWTON *and* H. F. DODGE†
Graphic Data Reduction Dept.
IBM, Kingston, New York

(*Abstract on page 169*)

INTRODUCTION

THE purpose of this paper is to describe an IBM 7094 Data Processing System program designed to produce fictitious photographic data. Such data are now being used as an important tool in carrying out research in digital automatic mapping at IBM.

In this research, an independent effort is being made to produce and verify techniques for automatically generating contoured orthophotographs from control-annotated stereo diapositives, ground control data, camera calibration information, exposure station position estimates, and output specifications. Current activity is largely concerned with finding a solution to the problem of automatically associating corresponding images on the several photos of the strip or block on which the images appear. Another objective is to establish specifications for practical special purpose equipment which will carry out orthophoto compilation automatically at high speed. One approach to an automatic mapping system is described in [1].

A stereoscopic pair of "photographs" of a hypothetical terrain model can be simulated, stored on magnetic tape, and printed for visual inspection.

PURPOSE OF FICTITIOUS DATA

The function of the fictitious data is to establish strong technical control over the correlation research. Digital means have been devised for generating fictitious terrain and photographic data about which everything is known. The fictitious terrain data are composed of both the gray-scale value and the exact geographic position (X, Y, Z) for ground points as close together horizontally as 0.1 foot. From such terrain data and from knowledge of exact position, attitude, and principal distance of the camera, values of which are arbitrarily chosen, fictitious photographic data with points as close to each other as one micron can be obtained. All photo coordinate data are accurate within the limits of round-off error. No presently available electronic scanning equipment can extract such error-free photo data. Moreover, it is impractical to attempt to obtain accurate geodetic positions for such a multitude of ground points in a real photo model.

The primary use of such error-free data is to facilitate the evaluation of the correlation program and to establish various decision-making criteria in the correlation process.

The main function of the fictitious photo-generation process is to introduce stereoscopic or binocular parallax into two photographs. In human stereoscopic vision, binocular parallax is the principal depth cue [2]. All other depth cues, binocular or monocular, such as linear perspective, monocular movement parallax, shadow patterns, interposition, etc., are of much less importance and merely serve

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† Mr. Dodge is now Principal Engineer, Recon. & Mapping Dept., Aeronutronics Div., Ford Motor Co., Newport Beach, Calif.

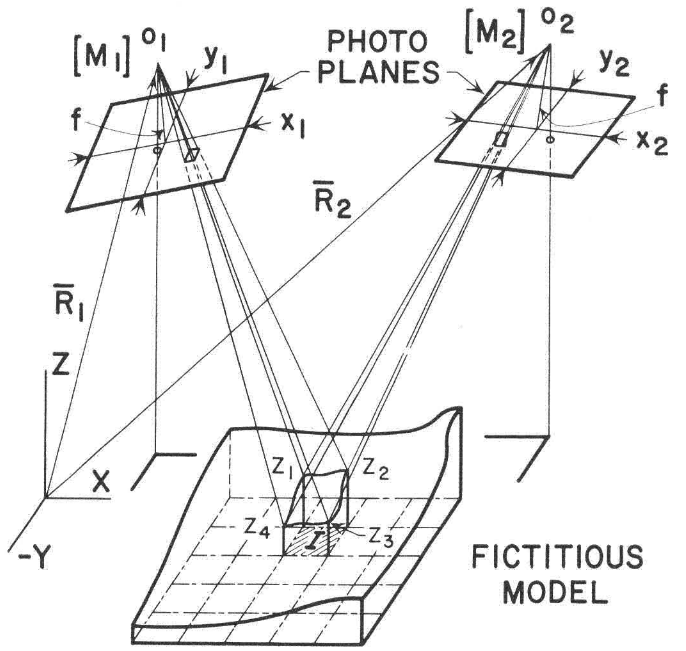


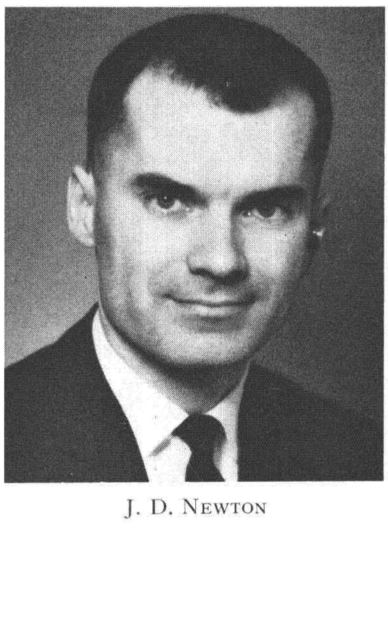
FIG. 1. Geometry of projection of model element to photo-planes. (*Text on page 168.*)

to help stereoscopic vision. The use of a random gray-scale pattern in a pair of fictitious stereo photographs demonstrates that stereo vision can be accomplished with only binocular parallax; a random gray-scale pattern is devoid of all other depth cues.

Therefore, any correlation process performed on the fictitious photos will have to utilize the property of binocular parallax in order to derive height information. No other depth cues need to be present in the photos. In fact, it does not appear possible or practical to devise a correlation process which will take advantage of depth cues other than binocular parallax, except in very restricted cases (e.g., in determining the height of moon craters from shadow cues on a single photograph).

If binocular parallax is the only depth indicator required in fictitious photographs, it is clear that the gray-scale pattern need not correspond to the elevation data in the ground terrain model in order to establish stereoscopic vision. This correspondence is likewise not required for current photo data correlation processes which make use of only the binocular parallax property.

Realistic errors can be inserted into the data. These errors fall into two categories: (1) gray-scale; (2) geometric. Gray-scale errors can be used to simulate noise, simulate uneven transmission of light through the atmosphere or lens, and simulate differences in reflectivity from the ground. The use of such errors tests the ability of the correlation program to adapt itself to normal photographic variations in film densities. Geometric errors which can be easily determined or described, such as residual aerotriangulation error and errors inherent in an electronic scanner, can also be introduced.



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When a satisfactory correlation program is developed, it is planned to introduce these arbitrary errors into the data. For design of an optimum mapping system, a series of tests can be run to determine the allowable errors in the electronic gear, the required spot size, and the gray scale quantization needed for any desired final accuracy. Trade-offs of these different factors can be investigated.

In all these tests, the fictitious data provide the framework within which controlled experiments can be conducted.

EVALUATION OF THE CORRELATION PROCESS

As previously mentioned, the fictitious data consist of ground terrain elevation data, two stereo photographs, the principal distance of the camera, and "aerotriangulation" data (the positions and attitudes of the two cameras at the time of exposure). In the automatic mapping program, only the two fictitious stereo photographs and the principal-distance of the camera are provided as input to the correlation process in its function of associating corresponding images. The quality of this process of association or correlation is checked by an evaluation routine. Evaluation proceeds as follows for each pair of correlated points:

1. The object rays are projected in accordance with the aerotriangulation data, with the camera principal-distance, and with the photo coordinates found by the correlation process; in this way, the position of the virtual ground intersection is found (i.e., horizontal and vertical position).
2. The ground model data are interrogated for the true terrain elevation at the horizontal ground position.
3. A comparison of the true elevation with that computed from the correlation process provides the basis for determining if vertical accuracy requirements have been met.
4. The original horizontal position of that ground point corresponding to one of the object rays, as selected by the correlation process, is obtained from the fictitious data.
5. A comparison of the original horizontal position with that found as a result of the correlation process forms the basis for determining if horizontal accuracy requirements have been met.
6. Horizontal and vertical errors are summarized by the evaluation routine.

To verify the fidelity of the test loop prior to the testing of a highly complex correlation program, it is expected that the loop will be closed first by using an "a-priori correlation program." This program will select, from the fictitious photo data, matched pairs of points as they are generated. When the entire test loop has been proved, the "a-priori" correlation program will be replaced by the actual correlation programs to be evaluated.

MECHANICS OF DIGITAL FICTITIOUS DATA GENERATION

The geometry involved in producing a fictitious stereogram, such as those given in Figures 5, 6, 10, 11, and 13, is illustrated in Figure 1 (shown on page 167). It will be shown how, over each photo plane, a discrete gray-scale picture pattern corresponding to a perspective photograph of the model can be generated. Each photo coordinate system is given any desired spatial position $\overline{\mathrm{R}}$ and attitude $\boldsymbol{M}$. ($\boldsymbol{M}$ is an orientation matrix whose values are direction cosines of the photographic coordinate system taken relative to the master ground X, Y, Z coordinate frame.)

The ground model is an arbitrary discrete surface defined on a square grid on the X-Y plane. Elevation information is given at each X, Y grid intersection. Figure 1 shows such elevations for a typical square element in the model. Such terrain data may be computed from a mathematical surface or interpolated from contour map data for a realistic effect. Any grid interval can be chosen for the model.

The gray-scale values for the model may be any arbitrary density pattern; in general, the gray values are obtained by electronic scanning of an aerial photograph. The gray values are assigned on the basis of one to a ground grid square. In the computer program, capability exists for carrying along 1 to 6 gray-scale values per ground square; thus, 1 to 6 different gray-scale density picture patterns may be assigned at one time to the relief model. When carrying out the stereo-projection process (see below), the 1 to 6 gray-scale values per ground grid square are carried along as a single entity. Hence, after the entire photo-plane projection process has been completed, 1 to 6 pairs of stereograms are obtained. These are all derived from the same ground terrain but have different picture patterns.

To generate a fictitious photograph, square elements along each row of the model are projected in sequence by the program to the photo plane (on which is superimposed a square photo grid). The projection equations used are those originated by von Gruber (1932):

$$x = -f\frac{M_{11}(X_G - R_X) + M_{21}(Y_G - R_Y) + M_{31}(Z_G - R_Z)}{M_{13}(X_G - R_X) + M_{23}(Y_G - R_Y) + M_{33}(Z_G - R_Z)}$$

$$y = -f\frac{M_{12}(X_G - R_X) + M_{22}(Y_G - R_Y) + M_{32}(Z_G - R_Z)}{M_{13}(X_G - R_X) + M_{23}(Y_G - R_Y) + M_{33}(Z_G - R_Z)}$$

in which

x, y are the photo-coordinates of the projected point
f is the principal distance of the camera
$\boldsymbol{M}$ is the orientation matrix of the photo-plane
(X_G, Y_G, Z_G) is the position of the ground point
(R_X, R_Y, R_Z, components of $\overline{\mathrm{R}}$) is the location of the camera exposure station

The four rays from the corner elevations of the ground-square element form the corners of a quadrilateral on the photo-plane as indicated in Figures 1 and 2. Next, the vertical (or horizontal) grid line intercepts (see intercept points, Figure 2) on the sides of the quadrilateral are obtained. The intersections of the square photo-grid within the projected quadrilateral boundary then consist of the points lying in between each corresponding pair of intercepts. These enclosed grid intersections (photo-points) are assigned the gray-scale density value (or values) of the corresponding ground-square element.

The photo-grid intersections with their associated gray-scale densities (spots) simulate the scan-by-scan and spot-by-spot discrete sampling of a photograph by an electronic-optical scanner. The photo-grid spacing corresponds to the spot interval (or spot size) of the scanner. Capability exists in the computer program for setting the photo-grid spacing (resolution) to any desired value. In general, a 1-1 ratio between the number of photo-grid intersections and the corresponding number of ground-grid intersections is maintained.

Because the photographic axes are not necessarily parallel to the master coordinate system and because of the usual presence of relief in the model, a sort-and-merge routine is required to order the gray-scale density values of the generated photo by spots in x and by scans in y. This routine takes up the bulk of computer time in generating a fictitious stereogram.

An a-priori correlation routine is included in the program to save the x and y coordinates of a large number of points projected up to each photo-plane, as corners of quadrilaterals. Matched pairs of points on the two photos are thus retained for later use in checking out other programs in the closed simulation loop.

The computer program provides for sequential numbering of the ground grid squares. These numbers are carried to one photo-plane along with the gray-scale values associated with the same ground-grid squares throughout the entire simulation process—stereo-projection, correlation, and evaluation. In this way, a horizontal check can be made on the correlation process. As a result of the correlation program, matched pairs of photo points are obtained; each pair of these is associated with a gray-scale value and with a ground-grid square number corresponding to one of the photo points. The horizontal error

ABSTRACT: *Techniques for generating digital fictitious stereograms on an IBM 7094 Data Processing System are described. The stereograms are obtained by a perspective projection of a ground model with known elevation and gray shade detail upon two "photo" planes with known spatial position and orientation. Realistic photographic and geometrical errors can be introduced into the data if desired. Such fictitious data are very useful for evaluation of digital automatic mapping programs now being developed and perfected at IBM.*

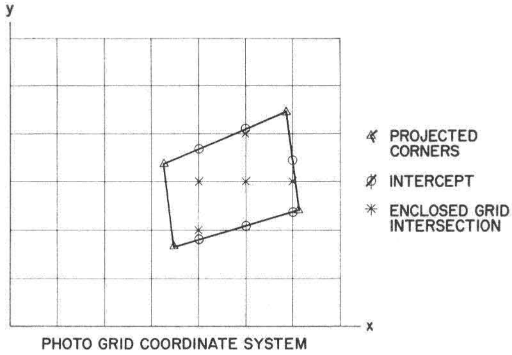

FIG. 2. Assignment of photo-grid points to a quadrilateral.

due to correlation is then given by the difference in position between the original ground-grid square (denoted by the grid square number) and the ground-grid square containing the position computed from the photo-to-ground projection of the correlated pair of photo points.

The fictitious stereograms are idealized in that gray-scale density variations do not exist for corresponding regions in the two pictures —if both pictures of a pair are derived from a relief model with the same density pattern. In real photography, such gray-scale density differences do exist because of differences in light reflectivity on the ground and different amounts of atmospheric haze for the two exposure stations; in addition, the corners of a photograph are made darker than the rest of the photograph because less light passes through the camera lens for these regions. To simulate real photography, the computer program incorporates a routine to interpolate fine ground-grid gray-scale density changes ($\pm$values) from gross grid data determined manually. The ground grid gray-scale density pattern may then be modified by these gray-scale changes prior to the generation of a fictitious photograph.

In addition to these gross changes made to gray-scale density, noise may also be introduced into the fictitious photo data. For this purpose, a random-number generator routine was devised. The muliplicative congruential scheme in use at MIT was adopted. It produces normally distributed noise ($\pm$values) with any desired mean and variance which become the changes to be made to the gray scale density pattern of a photograph.

The following geometric errors, present in any digital system, can also be introduced into the fictitious data to determine how they affect output accuracy:

1. Rotation error
2. Translation error
3. Linear and non-linear x, y position errors.

Rotation and translation errors occur when the photographic axes (fiducial marks) are not located where they are thought to be when setting up the photographic plates for scanning.

Because of electronic, optical, and mechanical errors in a scanner, linear and non-linear x, y errors in positioning the light beam result. This type of error can be measured and either entered in tabular form or approximated by 1-variable or 2-variable polynomials.

Aerial photographs often have features which appear in one photograph but are not visible in a second overlapping photograph. These "hidden" features occur whenever ground terrain slope is sufficient to obscure the terrain from a camera exposure station.

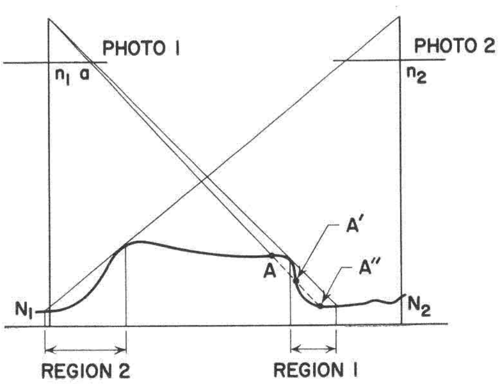

FIG. 3. Hidden features.

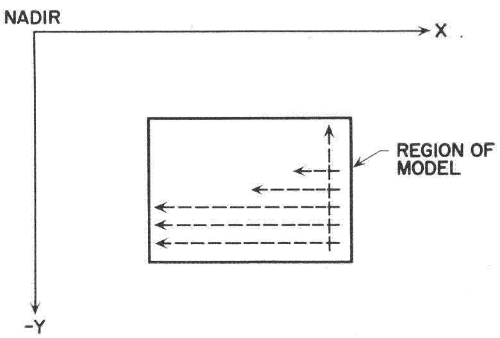

FIG. 4. Projection sequence of model elements.

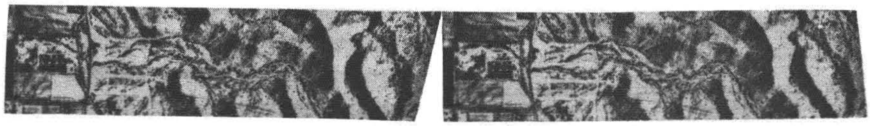

FIG. 5. Fictitious stereogram derived from a photo pattern superimposed on mathematical model.

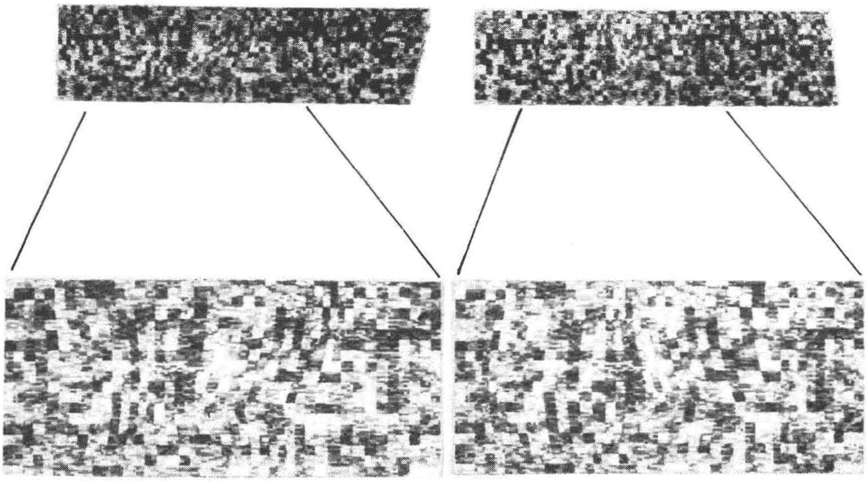

FIG. 6. Fictitious stereogram (with enlarged section) derived from a random number pattern superimposed on mathematical model.

In Figure 3, for example, region 1 is hidden from photo 1 and region 2 from photo 2. In the region of a hidden feature, three ground terrain points (two at points of tangency) project along a single object ray to a single point on the photo (e.g., points A, A', A'' project to point a, Figure 3), whereas only one point, point A, is visible. To insure that only the visible points are projected onto the photo, the computer program always projects ground-square elements in a sequence moving inward toward the ground nadir point (for the given photo-plane) from the outermost corner of the model, inward in spots along a scan, then inward to the next scan, etc. (Figure 4). In the computer program, each photo grid intersection receives only the *last* gray-scale density value that is assigned to it. In the two dimensional illustrations of Figure 3, point a on photo 1 is assigned first the gray-scale value from point A'', then from A', and finally from A, when the projection sequence is taken from right to left toward the nadir point N. The projection

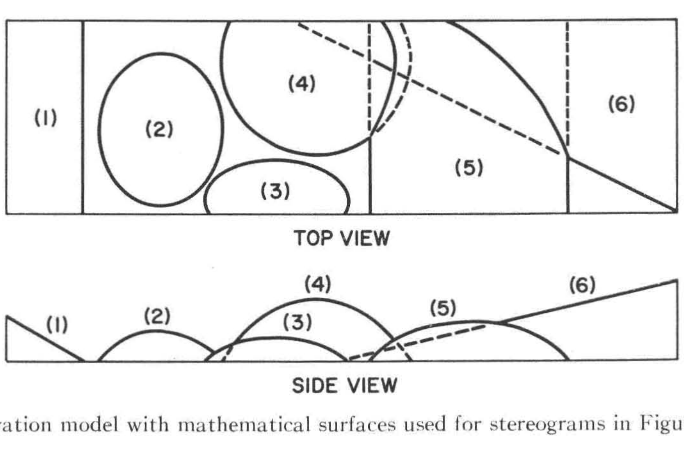

FIG. 7. Elevation model with mathematical surfaces used for stereograms in Figures 5 and 6.

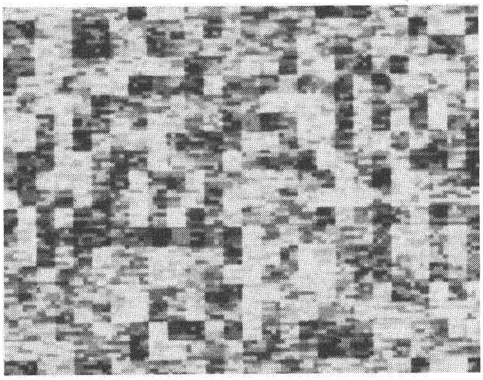

FIG. 8. Ground random number pattern for stereograms in Figures 10 and 11.

sequence therefore assures that only the visible gray-scale density values are transferred to the photo-plane.

TABLE 1

Surface	*Surface Numbers*
Ellipsoid	1, 3, 5
X cylinder	2
Inclined plane	16
Elliptical paraboloid	All remaining surfaces

Real photography has certain properties which are not simulated by the fictitious data generator. These are:

1. Multi-valued elevation data. In real photography, many situations exist in which three elevations are required to describe an object at a given horizontal position. For example, detail under a tree or under an overhanging roof of a building can be seen. The fictitious data generator, as designed, can only repro-

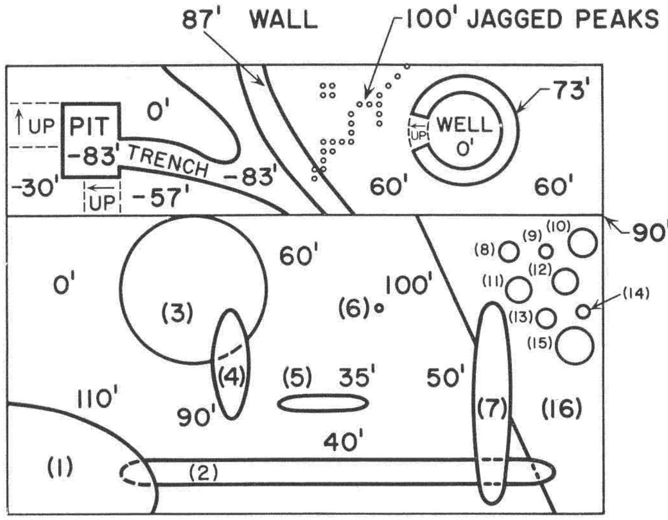

FIG. 9. Terrain model for stereograms in Figures 10, 11, and 13.

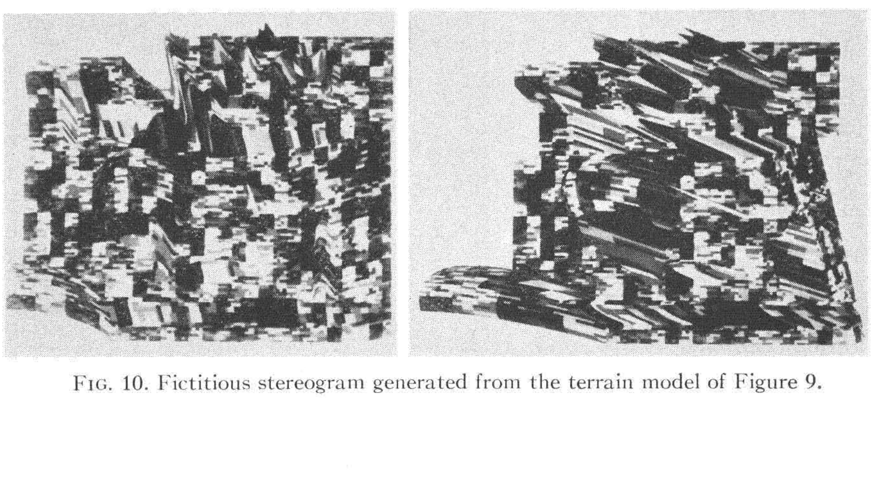

FIG. 10. Fictitious stereogram generated from the terrain model of Figure 9.

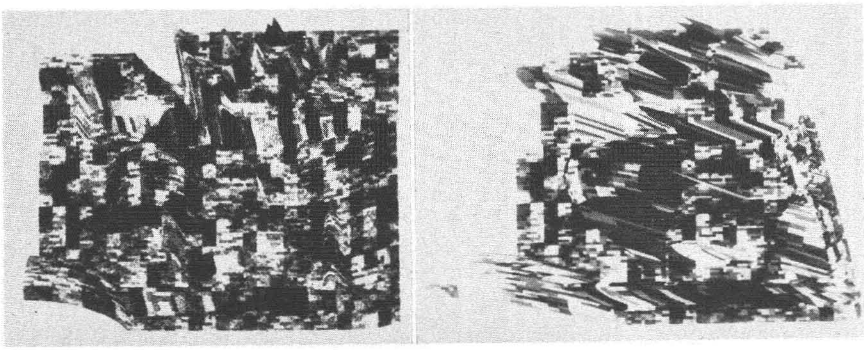

FIG. 11. Stereogram of Figure 10 modified by noise and gross gray scale changes.

duce ground terrain with slopes of less than ± 90 degrees.

2. Shadow effects. With additional programming, shadows probably can be introduced into fictitious photo data, if desired.
3. Individual local gray shade variation due to differences in reflectivity. This property is simulated only crudely by the use of gross gray-scale changes and normally distributed noise.
4. Those photographic errors which cannot be adequately defined.

A most realistic fictitious model, in which the photo patterns correspond to the terrain data, can be generated. It would make use of a digital photo-data correlation program as follows:

1. The correlation program is used to generate two outputs upon correlating a given stereo pair of real photographs; these are:
   (a) terrain elevation data
   (b) an orthophoto based on orthocorrection of one of the two photographs.
2. Using a terrain model made up from these two outputs of the correlation program, two stereo fictitious photos are generated.

It does not matter if the correlation program produces elevation data which is inaccurate with respect to the actual terrain because these data are now being defined as being "true" terrain data for the fictitious model.

A second way to obtain a realistic model requires a large amount of manual work. The steps required are:

1. Contour lines from a contour map are transferred to one of the two photographs while viewing the diapositives in stereo.
2. Fine grid elevation data are interpolated from gross grid elevations extracted from the warped contour map overlay on the given photograph.
3. Using a terrain model consisting of the fine grid elevation data and the given photograph gray pattern, a fictitious stereogram is generated.

EXAMPLES OF FICTITIOUS STEREOGRAMS

Figures 5, 6, 10, 11, and 13 are fictitious stereo photographs prepared on an IBM 7094-II computer. All are vertical photographs. All gray-scale patterns have a range of eight shades of gray (0 to 7).

Figures 5 and 6 are fictitious stereograms prepared with the same terrain elevation data but with the different gray-scale patterns shown. The elevation data is composed of the six mathematical surfaces indicated below and appearing in Figure 7, from left to right:

1. Side plane
2. Elliptical paraboloid
3. Ellipsoid
4. Elliptical paraboloid

FIG. 12. Ground photo pattern for stereogram in Figure 13.

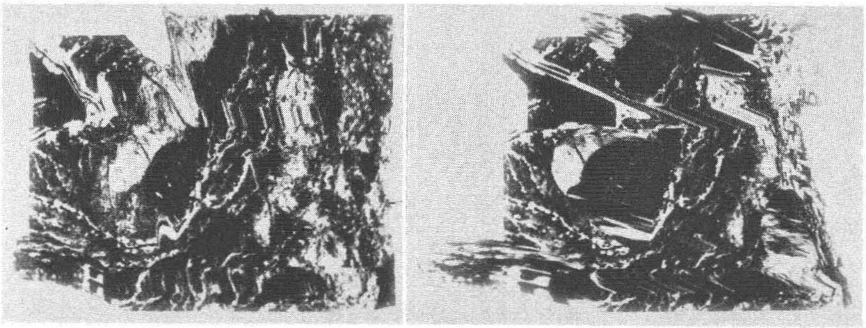

FIG. 13. Stereogram with photo pattern modified by noise and gross gray scale changes.

5. Elliptical cylinder running up and down
6. Inclined plane in upper right corner

The use of a random number pattern in Figure 6 shows that stereoscopic parallax provides the only depth cue in the stereogram.

Figure 8 shows the basic ground random number pattern used for the stereograms in Figures 10 and 11. The terrain model for Figures 10, 11, and 13 is shown in Figure 9. In this figure are depicted the rough outlines of surfaces which can be seen in the stereograms. The elevation model consists of an upper and lower section. The upper section is fine grid elevation data which was interpolated from gross grid elevations manually assigned and is generally self-explanatory. The lower part consists of mathematical shapes given in Table 1.

Figures 10 and 11 are the same stereogram except that normally distributed noise (with mean 0 and standard deviation 1.2) and gross gray-scale changes (ranging from +2 to −3) have been introduced into the left and right photos of Figure 11, respectively.

TABLE 2

	Time (Minutes)	
Generate ground model elevation data (640×480 spots)	6.3	
	Left Photo	*Right Photo*
Generate unsorted photo data	10.5	16.0
Merge and sort photo data	36.0	36.0
Introduce gross gray scale changes		3.6
Introduce gray scale noise	3.0	
Prepare data for recording on film	13.6	13.6
Total for stereo photo (minutes)	63.1	69.2

For the stereogram of Figure 13, the basic ground pattern used was that of Figure 12. The same terrain data (Figure 9) used for Figures 10 and 11, is used in Figure 13. As in Figure 11, noise and gross gray-scale changes are included in Figure 13.

While all features in Figures 5 and 6 in both the left and right photos are clearly visible to the eye, there are ground features which are hidden from both photos in Figures 10, 11, and 13. This may be seen by comparing the latter with Figures 8 and 12, the original ground gray-scale patterns. Close examination of Figure 10 will disclose features visible in the left photo but not in the right photo.

Because (1) the elevation changes in the terrain model (Figure 9) are quite large and (2) the model is located in the upper left quadrant relative to the ground nadir points of both camera stations, large binocular parallaxes result. Since it is quite difficult to view stereograms 10, 11, and 13 in stereo and because they overlap, they are not mounted for easy stereo viewing. Nevertheless, these stereograms are interesting when viewed monocularly. The terrain features are clearly identifiable. (This is particularly true in the case of Figure 10.) It is apparent that when hidden features are present, the monocular depth cue of interposition (the superimposing of near objects upon far objects) comes into play [2].

Total running times on an IBM 7094-II for the stereograms in Figures 10, 11, and 13 are shown in Table 2.

Summary

This paper has shown how fictitious stereo photography can be generated on a general-purpose digital computer. A fictitious terrain model must first be constructed from an arbitrary gray-scale pattern and an elevation model. The elevation data can be interpolated from a contour map or from manually assigned elevations, or it can be computed from mathematical shapes. A fictitious stereogram is then easily obtained by the mathematical projection of the terrain model upon two tilted photo-planes in space.

Such fictitious data can be utilized as a powerful tool in research on digital correlation techniques. Since most correlation techniques under investigation today for use in automatic map compilation employ only the binocular parallax property as a clue to depth, the lack of correspondence between gray-scale pattern and elevation data, the absence of shadows, and the inability to reproduce the wide variety of tonal differences between the two photographs (which are present in real photography) are not detrimental to correlation research. Neither is the inability to generate multi-valued terrain data considered a significant disadvantage.

Acknowledgments

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