PHOTO-COMPUTER PLOT MONTAGES FOR HIGHWAY DESIGN

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A photo-computer plot montage is a composite picture made up of a computer-drawn perspective and a photograph. The purpose of the montage is to depict a proposed construction work, in this paper a highway, as well as its surroundings as it will appear when completed. It is the contention of the authors that, although a perspective drawing or an artist's sketch may not be detailed and extensive enough to be used for aesthetic judgments, the photo-plot montage is; and, with the system described, which introduces photogrammetric resectioning as a means of finding the photograph perspective parameters, photo-montage is brought within the reach of the design engineer for everyday use.

•AS THE SCALE of engineering works increases, so does the visual impact they have on their surroundings. The modern highway, with its high-speed alignment and wide carriageway, is, of necessity, a massive structure that tends to dominate all but the most rugged scenery.

The highway engineer should evaluate carefully the finished appearance of his design and its harmony with the landscape. He needs visual aids to depict the finished work and its surroundings for his own work in design and also for presenting his design to others.

Over the past few years much effort has gone into the development of computer systems to make perspective drawings. A number of fields, including mathematics, molecular chemistry, flight training, and, quite notably, highway engineering, now use computer-generated perspectives more or less routinely. The linear form of a highway lends itself to this process, and, when terrain and design data are already available from an automated design process, perspectives can be generated readily and economically. A drawing can be computed from the terrain and template data, from a specified perspective center and direction of line of sight, and drawn by incremental plotter or projected onto a cathode ray tube (CRT).

Several researchers (1, 2, 3, 4, 5) have systems for generating highway perspectives. Of these, Godin et al., using the TE.GI program (4), and the joint Federal Highway Administration-University of Colorado group (5, 6, 7) have also made animated movies by photographing a succession of views drawn from a moving "driver's eye" viewpoint.

However, the entirely machine-drawn view is not complete enough to realistically picture a highway and its surroundings. It is in fulfilling this needed environmental role that the photo-montage has promise. A photograph of surrounding terrain (Fig. 1) can be merged with the machine-drawn perspective of the construction (Fig. 2) to form a photo-montage of the completed work (Fig. 3).

The problem in making the montage is to match the two component pictures without relative distortion. This requires that both have the same scale, perspective center, and line of sight. Inasmuch as these three parameters are required data in the computer generation of a perspective, it is necessary to determine them for the photograph to be used in the montage. This can be done in two ways. First, the photograph can be taken by phototheodolite, with the parameters measured by careful surveying for each photograph. This procedure has been used successfully in a University of Tokyo system and has been described by Nacamura (8).

Figure 1. Photograph of existing terrain and old highway, Colo-7.

Figure 2. Computer-generated perspective.

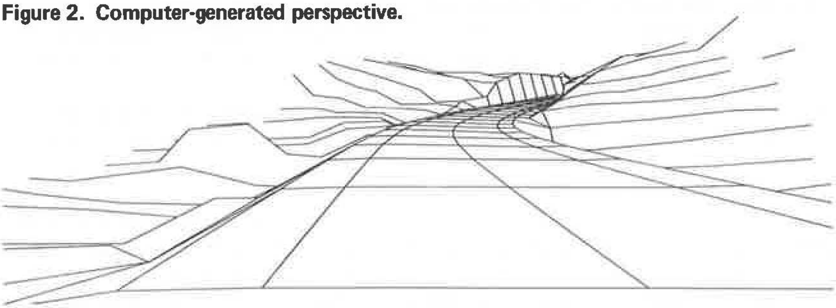


Figure 3. Montage of Figures 1 and 2.

A second method, developed at the University of Colorado (9), allows photographs to be taken at random and the perspective parameters recovered later by photogrammetric resectioning. Resectioning requires only that the position of three well-defined points in the photograph be known. This approach allows much more freedom in selecting views and reduces the capital investment and field time required to produce montages. The authors believe that this development brings photo-montage within the reach of the practicing engineer. The steps in the Colorado process are shown in Figure 4.

MATCHING THE PERSPECTIVE AND THE PHOTOGRAPH

Exact matching of the two component parts of the montage is achieved, excluding lens and film distortion, if they have the same scale, perspective center, and line of sight. These terms are defined in Figure 5, which shows the geometry of the perspective projection. The position of the perspective center and the orientation of the picture plane, described by the direction of the line of sight, which is normal to it, determine the perspective of the drawing. The scale is directly proportional to the focal length, which is the distance between the picture plane and the perspective center. Thus the perspective and scale of the drawing are completely described by the three parameters: focal length, perspective center, and line of sight. They also serve to describe the identical geometry of the photograph.

Acceptable tolerances, to produce a satisfactory montage, must be established for each of these three fundamental perspective parameters. These tolerances will then be used as a standard for the resectioning program.

Errors in scale do not present a practical problem, inasmuch as the focal length of the photograph is generally known to sufficient accuracy for a particular camera. If not, it can be determined as an additional unknown in resectioning. Small errors in the line of sight also cause no difficulty. It can be shown (9) that, for a photograph of focal length f and with an angle $\delta\alpha$ between the two lines of sight, an image displacement Δ_{max} given by

$$\Delta_{max} = 1.16 f \delta\alpha \tag{1}$$

is produced. Consequently, for a large error of 1 deg in the line of sight, the resulting maximum image distortion on an 18- x 24-in. enlargement (f = 25 in.) is 0.05 in., which is tolerable.

However, the montage is quite sensitive to errors in the perspective center coordinates. It can be shown (9) that an error in the perspective center in a direction transverse to the line of sight, say the x-direction, will produce an image displacement Δ_x in the corresponding x-direction in the photograph. Image displacement is also produced in points off the line of sight by an error in the perspective center in the direction of the line of sight, the D-direction, but to a lesser extent. The total image displacement in the x-direction is given by the expression

$$\Delta_x = \frac{f}{D}(\delta C_x + \beta\, \delta C_D) \tag{2}$$

where

- D = distance to the object point in space,
- δC_x = perspective center error in the x-direction,
- δC_D = perspective center error in the direction of the line of sight, and
- β = angle subtended at the camera by the object point and the line of sight.

β is limited by the camera field of view to about 20 deg or approximately 0.35 rad. Thus, the contribution of an error along the line of sight is limited to, at most, about one-third of that due to the same error in a transverse direction. Also, inasmuch as the distortion is inversely proportional to the object distance, the foreground will be affected much more than distance points. For example, an error of 1 ft in the x-direction would cause distortion of $\frac{25}{50} \times 1 = 0.5$ in. in the image of a point 50 ft distant

Figure 4. Photo-plot montage system.

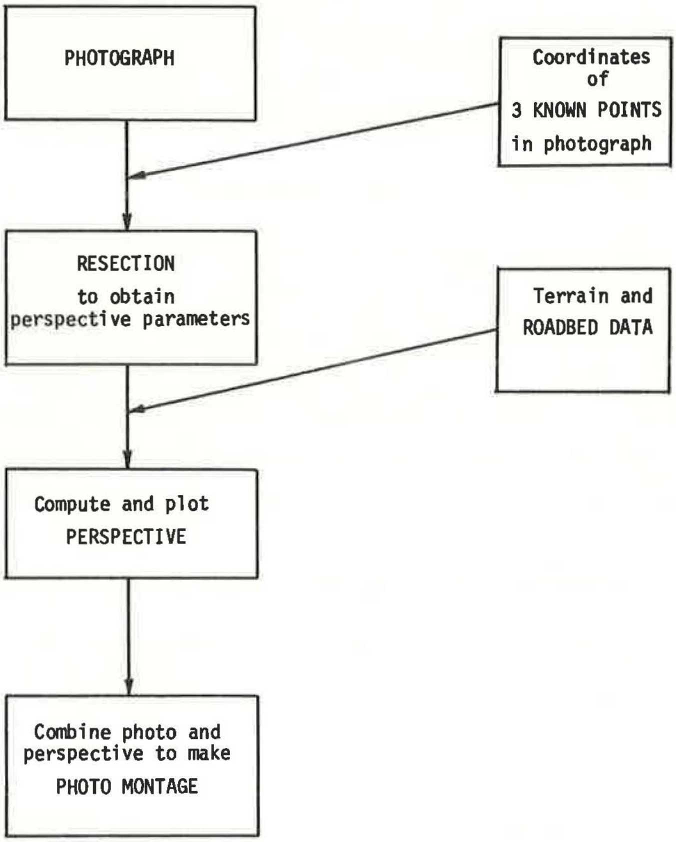
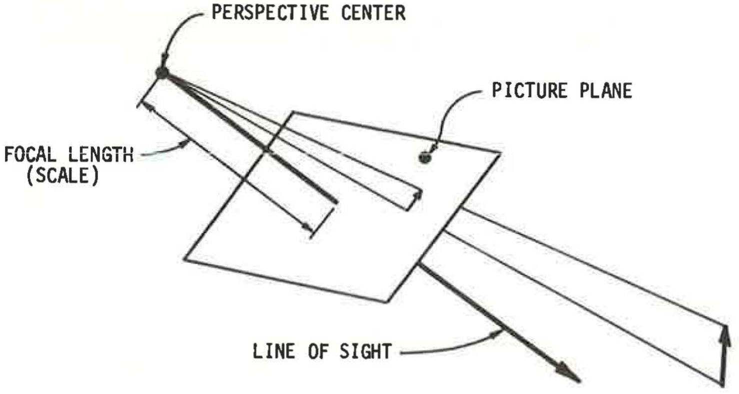


Figure 5. Perspective projection.



but only $\frac{25}{500} \times 1 = 0.05$ in. in the image of a point 500 ft distant. This accentuation of foreground distortion is partly compensated for by the eye, which is more critical of mismatching in the distance than it is in the foreground.

From the foregoing, it would seem reasonable to propose the following tolerances: line of sight, ± 1.0 deg; and perspective center location, ± 0.5 ft transverse to line of sight and ± 2.0 along the line of sight.

THE PHOTOGRAPH

The photographs shown were taken on glass plate negatives using a Wild P-30 theodolite in order to eliminate film and lens distortion as variables while developing the system. However, such a high-precision camera and film are not necessary. A 2¼- x 2¼-in. Rollei roll film camera, with a glass plate added to carry fiducial marks and to keep the film flat, has been used successfully in Sweden (10) for architectural mapping that required precision similar to that of photo-montage. Being able to use such a camera that is compact and easy to handle makes the method all the more attractive. In addition, montages have been made using a 4- x 5-in. sheet film camera with good results.

All the trial montages made used commercial 18- x 24-in. enlargements, and the resectioning points in the photograph were measured from contact prints by a vernier rule reading to $^1/_{1,000}$ in.

RESECTIONING

The procedure of calculating camera position and orientation from the known position of three points and their image in a photograph is called resectioning. It has been known in photogrammetry since about the turn of the century and has been widely used in analytical photogrammetry, particularly since the advent of the digital computer.

The coordinates of a point in space, the coordinates of its image in a photograph, and the position and orientation of the camera are related by a pair of equations, known as the projective transformation equations. Because there are six unknowns in the resectioning problem, three camera coordinates and three angles defining the line of sight, three pairs of equations must be solved simultaneously. Because these equations are nonlinear and involve trigonometric functions, the solution is not a trivial task.

In photogrammetry it is usual to take more than the necessary three points and use a least-squares method of solution. However, because the camera is much closer to the known points in the photo-montage application, a least-squares error reduction is not necessary. Newton's method of solving nonlinear equations has been used in the Colorado program (11).

Tests in typical photo-montage situations showed that, given normal surveying accuracy and provided the resectioning points are not bunched too closely together (as are the group of points shown in Figure 6), the camera position could be obtained to within ± 0.10 ft and the line of sight to ± 0.1 deg. These tolerances are well within those proposed above.

For a history of resectioning, the reader is referred to Doyle (12) and, for more details of the procedure, to any standard textbook of photogrammetry, such as Hallert (13).

COMPUTER-DRAWN PERSPECTIVES

The Colorado perspective programs (14, 15, 16, 17) take terrain and road template data in the form of the Federal Highway Administration's earthwork output (18), together with the perspective parameters obtained by resectioning. The perspective program generates a file of plot data that may be read by either a CRT display driver program or an incremental plotter driver to produce a pen-and-ink drawing. The known points are marked on the plot to enable it to be aligned with the photograph.

Completing the montage is then a matter of cutting off the areas of plot that do not depict new construction and pasting the plot over the photograph. Figure 7 shows a montage of the highway pictured in Figure 6.

Figure 6. Photograph of existing highway with resectioning points.

Figure 7. Photo-montage of Figure 6.

The cost of producing montages such as those shown in this paper includes a number of components whose individual costs highly depend on the particular organization involved and on the computer system used to perform the necessary computations. The following five components are identified:

1. Photographs that contain identifiable points on the ground;
2. Ground survey work to obtain coordinate information for the ground points;
3. Resectioning to obtain perspective-photograph information;
4. Cost of generating perspective view, including data file preparation, actual perspective generation, and plotting of perspective view; and
5. Fitting of the perspective plot to the photograph.

Our experience has shown that the computer costs using a CDC 6400 system range from $1 to $5 per view, depending on the availability of the needed design data files.

CONCLUSIONS

There is a need in highway engineering for graphic aids to depict the finished appearance of proposed highways. This need is heightened by the increasing concern in all quarters for environmental quality. With the use of resectioning to simplify and increase its versatility, the photo-montage system presented here goes a long way toward meeting this need.

Recently, some color montages have been produced, and it is obvious that the addition of color has made the process very valuable for communication with interested parties outside of the design group.

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