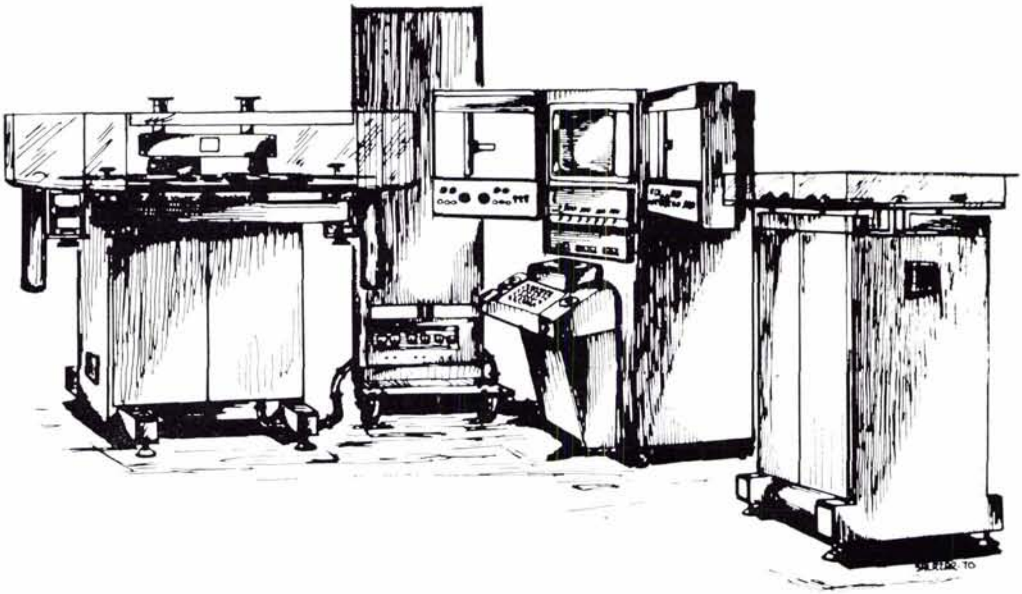

FRONTISPIECE. The Gestalt Photo Mapper.

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Image Correlator Speed Limits

The Gestalt Photo Mapper is an automatic orthophoto printer whose speed provides a substantial economic advantage over manual methods.

(*Abstract on next page*)

INTRODUCTION

WHY AUTOMATE photogrammetry? Many aspects of photogrammetry are enjoyable and at the same time economical. However one large part of the mapping process is somewhat unpleasant. Although compilation has interesting and creative aspects which attract young people to our industry, the never-ending task of terrain following must be repelling. Surely, the elimination of the eye-burning tedium of terrain following from photogrammetric compilation is a reasonable motive for automation.

Let us change from the plotter operators' point of view to the position of mapping organisations' management. The prime reason for any automation is economy, and photogrammetric automation must yield some measure of economic advantage if it is to be useful. Current manual plotters are relatively inexpensive but the labor cost involved in compilation is quite high. It seems that greater economic gain is available through the acceleration of processing than through the development of less expensive hardware. Thus, the economic motive for automation demands that we process map products faster to utilize

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the available labor more efficiently.

Since 1950 a series of developments has been directed toward reducing the human effort required for compilation. Some of these endeavors have dealt with peripheral areas such as numerical data handling and differential rectification. Some have dealt with the basic problem of stereoparallax clearance and the automation of the stereo-plotting function. The automation of topography by profile and contour plotting was reported in 1959. The advent of orthophotography has recently opened the way for the automation of planimetric compilation also, and automatic orthophoto printers are now produced by several firms. However, automatic plotters developed to date have not been sufficiently productive to offset their considerable cost increase over manual instruments. As you know, researchers are not easily put off by failure, so the search for higher speed goes on. At Hobrough Limited, we have developed a new insight into the basic root of the speed problem. In this paper we would like to show the results of the application of our approach.

ABSTRACT: *The tedium of photogrammetric compilation is a reasonable motive for automation. Inasmuch as plotters are relatively inexpensive and the labor cost of compilation is quite high, it seems that greater economic gain is available through the acceleration of the process rather than through the development of less expensive hardware. Because of the slowness of polynomial representation of terrain form, a* Δ *h matrix representation (gestalt: form, shape) which gives a large correlation zone and a large printing is offered. The Gestalt (ortho-) Photo Mapper attains the speed and accuracy to make automatic stereo compilation practical.*

SCOPE OF THIS PAPER

We shall not attempt here to prove the economic advantage of high-speed automatic compilation, but rather show how we have found it possible to achieve high speed. We believe that stereoimage registration is the central issue in the automation of photogrammetry and, in the first part of the paper, we shall outline the function of automatic registration systems. We shall endeavor to show that the performance of such systems in compilation instruments is directly related to the complexity of their transformation capability. We have found that transformation capability is in turn directly related to the ability of the system to store terrain form data and we shall outline the developments to date with respect to both transformation and memory. We shall deal principally with the application of automatic image registration to orthophoto printing although the arguments apply with little change to topographic automation. In the second part of the paper we shall describe a fast orthophoto instrument developed at Hobrough Limited in Vancouver, Canada.

DEFINITIONS

Let us define some of the terms used in this paper.

Image Registration. Image registration is the clearance of parallax between stereoimages over an extended area.

Correlation Range. There is a limited range of parallax within which a correlator can derive a useful parallax signal. We call this the *correlation range* and extend it equally for positive and negative parallaxes.

Correlation Zone is the area of the image under correlation at any instant. The correlation zone projects into model space as a more or less horizontal figure having a vertical thickness equal to the correlation range.

Transformation refers to a change induced in the shape of one or both of the stereo images of a correlation zone. The purpose of transformation is generally to achieve registration of the stereo images over the area of the zone. Such transformation has the effect of tilting or warping the correlation zone in model space so that it may conform more closely to the surface of the terrain.

It is necessary to differentiate between image data and terrain form data. We make the following distinction:

> *Image data* are the data stored in the aerial photos and are the input to the image registration system.
>
> *Terrain-form data* on the other hand are the output of an image registration system. In all automatic systems some means must be provided for the temporary storage of the terrain form within the correlation zone.

Two means are avaiable for representing terrain-form data for storage: the polynomial and the matrix representations.

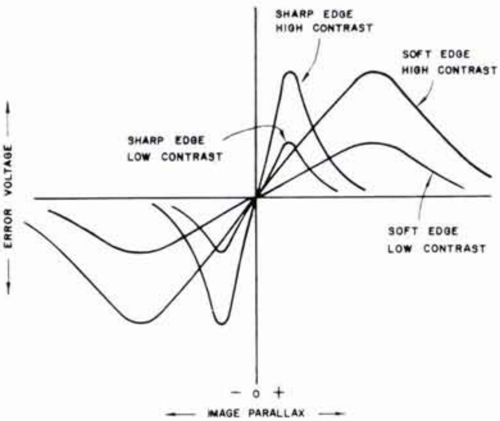

FIG. 1. Parallax discriminator characteristics.

Polynomial representations is the representation of terrain form by a polynomial in XY. The coefficients of the polynomial determine the shape of the surface approximation. In an instrument employing polynomial representation the coefficients must be individually stored in some form of memory.

Matrix representation is the representation of terrain form by means of a matrix of Δh values with respect to an assumed horizontal reference plane. In an instrument employing matrix representation the Δh values must be stored in some form of memory.

It can be shown that for a given complexity of terrain form the size of the memory required is approximately the same for both polynomial and matrix representations.

ELECTRONIC IMAGE REGISTRATION

Recalling the definition of image registration as clearance of parallax between stereo images over an extended area let us consider two questions: "Why clear parallax to zero rather than measure it?" and "Why do this over an area rather than at a single point?"

To answer the second question first: A single point cannot be identified in an image because it has only one variable: density. That variable would naturally be equal at many points in the image. On the other hand, the densities of a matrix of say 10×10 image elements is unlikely to be duplicated in an image and could therefore serve as a signature or identifying pattern. In general then, an area of image is required for correlation and the larger the area the more sure the correlation, provided that the images are identical in form.

Regarding the first question: "Why clear the parallax at all?" Why not just estimate parallax between images and use this information directly? The answer is quite simple; the magnitude of a parallax signal, say, from a single light to dark transition depends not only on the amount of the parallax but also on the sharpness of the image and its contrast. Figure 1 shows the effect of image characteristics on parallax error signals for typical correlations. It can be seen that all the error curves pass through the origin and therefore the error voltage can provide a reliable indication of the direction of image displacement. However, the voltage does not define the magnitude of the displacement unless one knows which of the four curves it is on, that is to say, unless local image characteristics are known. On the other hand, if the error voltage is zero the parallax has unequivocally been defined as zero.

An image correlation system examines pairs of photographs and many transform them to reduce parallax to zero over a large area. The amount of transformation required to register the images is stored in some form of memory, and if all parallaxes are reduced to zero the amount of transformation or motion required can be recalled from memory and related to Δh. Some type of terrain-form memory is required in all stereo plotters.

Figure 2 shows a basic stereoimage registration system. The scanners give video signals from which the parallax discriminator derives a signal representing instantaneous parallax. The analyzer gives instantaneous polynomial coefficients or Δh values from the fluctuating parallax signal.

In general the signals from the analyzer will be noisy and time-variable although the terrain form represented by these signals is naturally stationary. It is the function of the memory to smooth each of the signals from the analyzer and to hold their final values more or less continuously during the correlation process. The smoothed persistent signals from the memory are applied to a transformation system which causes the scanning pattern in the scanners to assume relatively distorted shapes.

It can be seen that the system described is inherently a feed-back system. Assuming that the left and right stereoimages are significantly dissimilar, parallaxes will be sensed upon commencement of scanning. The form analyzer will deliver to the memory signals representative of magnitude and direction of those parallaxes at various points within the scanned area. As the process proceeds and image transformation takes place, the magni-

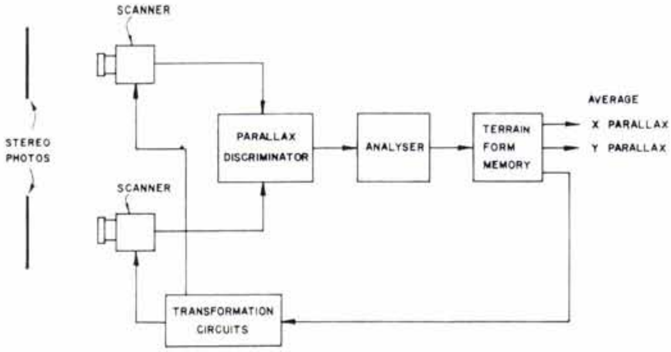

FIG. 2. Stereo-image registration system.

tude of parallaxes developed will gradually be reduced until, finally, the memory will contain essentially all the data required to transform the scanning patterns to the extent that the parallax and the form analyzer signals will fall to zero.

DEVELOPMENT OF STEREO CORRELATION TECHNOLOGY

The earliest correlators were able to sense X- and Y-parallaxes as averaged over the entire correlation zone. Such correlators could deliver only two error signals, one representing X-parallax, the other representing Y-parallax. Similarly, the memory was quite simple, generally consisting of integrators for the X- and Y-error signals. In some instruments the memory of parallax and terrain-form data were provided chiefly by the instantaneous position of the mechanial elements of the plotter. In such instruments the correlation zone is not transformed in the left or right scanners with the result that the projection of the correlation zone into model space produces a horizontal surface. Mr. G. L. Hobrough developed the first successful image correlator (Stereomat I) which was of this type.

Figure 3 illustrates the limitations of a horizontal correlation zone in rough terrain. The correlation range is shown as a vertical thickness (a) of the correlation zone. It can be seen from this figure that only a small part of the terrain (b) may lie within the correlation range and be able to deliver useful parallax signals. The result is reduced efficiency of sensing and an increase in the probability of complete correlation failure wherein the zone leaves the surface entirely.

The next stage in the development of electronic image transformation (Stereomat II) saw the addition of a means for first-degree polynomial image transformation. The result of a first-order transformation is that the correlation zone can be tilted in model space to lie more or less tangent to the surface of the terrain. Figure 4 illustrates the attitude of a correlation zone having a tilt capability under a variety of terrain conditions. It can be seen that the effective area or the correlation zone is considerably increased.

The addition of a first-degree transformation capability to electronic correlators improved the performance of automatic stereo plotters significantly with only a modest increase in correlator and memory complexity. An instrument employing first degree polynomial transformation requires only two additional memory circuits for storing the signals representing the slope of the terrain in the X- and Y-directions. These signals cor-

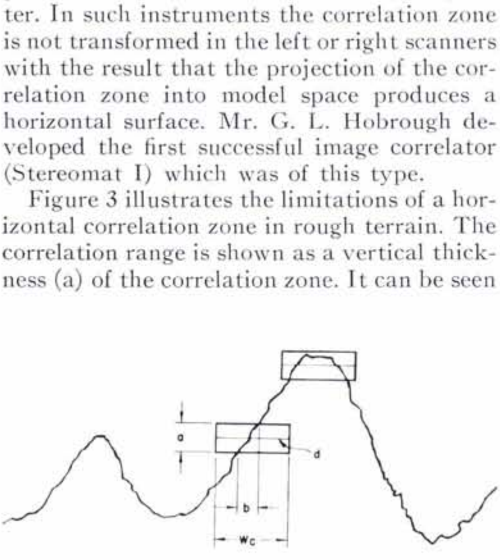

FIG. 3. Horizontal correlation zone in rough terrain.

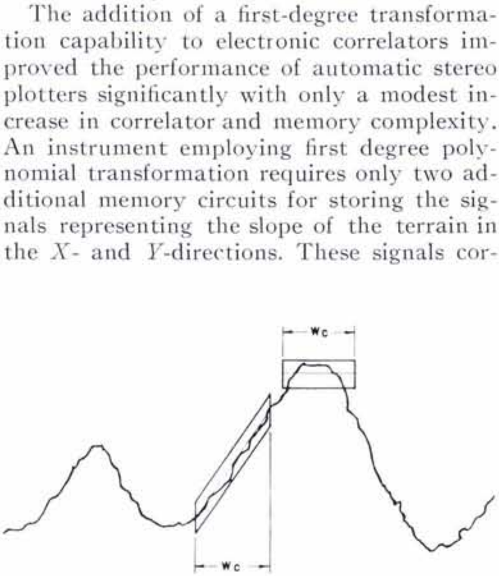

FIG. 4. Tiltable correlation zone in rough terrain.

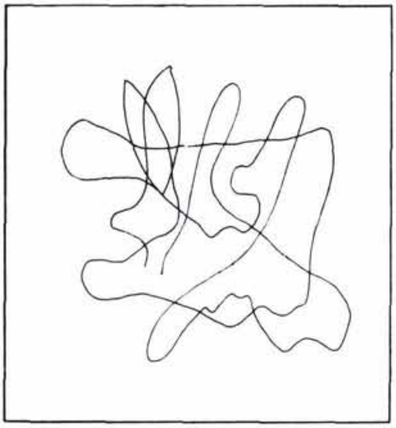

FIG. 5. The random scan.

respond to the first degree coefficients of the polynomial.

Let us consider for a moment the various scanning patterns used in electronic image correlators. The earliest Stereomats used a random scanning pattern (Figure 5) in which the scanning spot moves in all directions more or less randomly. Unfortunately, a random pattern is not well suited for electronic image transfer and it was difficult to adapt these instruments to orthophoto printing. The square lisajous pattern shown in Figure 6 used in the Itek Ares viewer can produce high-quality images but it required a large video bandwidth and a very precise registration of the four superimposed images produced. The most familiar form of scanning pattern is the TV raster shown in Figure 7. The Bunker-Ramo UNAMACE uses the TV raster. Until recently difficulty in sensing Y-parallax has limited the usefulness of the TV raster. However, it is probably the best pattern from the point of view of electronic image transfer.

This has been a very abbreviated view of the development of automatic plotters. We have shown that correlators have become more accurate as the effective correlation zone has increased. We have not discussed specific instruments in detail but rather generations of instruments. Details of individual instruments may be obtained readily from the literature.

Automation of Orthophoto Printing

In the introduction to this paper we mentioned that the advent of orthophotography has opened the way for automatic map compilation. The earliest automatic plotters compiled only topographic detail; first as profiles, later as contours. Because planimetric compilation for line maps requires a solution to the pattern-recognition puzzle, automatic planimetric compilation became feasible only with the acceptance of orthophotos as a map product. All current automatic plotters are, we believe, capable of orthophoto production. We shall discuss automatic orthophoto printing in some detail because it promises to become the primary automatic mapping process.

Two methods are available for printing an orthophotograph electronically: the *slit* method and the *patch* method. In the *slit* method a sensitized film is traversed continuously by an exposing slit having a length approximately equal to the longest dimension of the correlation zone. The printing of the orthophoto is a continuous process and height corrections generated by the correlation system are applied continuously while traversing the model. We believe that all current instru-

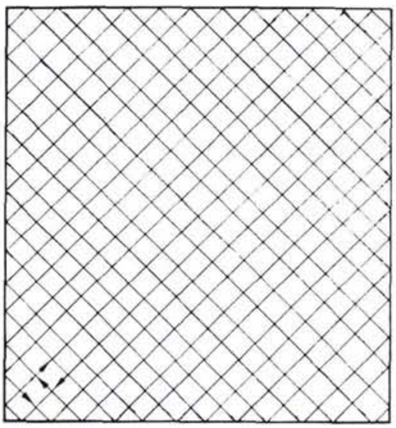

FIG. 6. The square Lisajous pattern.

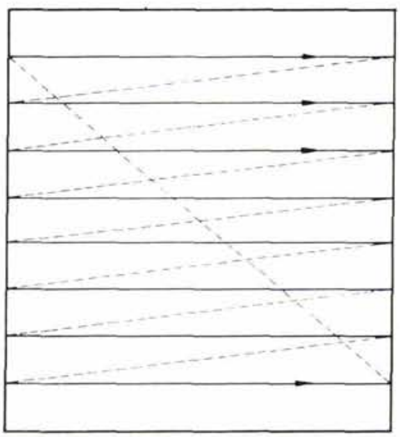

FIG. 7. The TV scan.

ments use the *slit* method of printing. We have developed a *patch* method in which the sensitized film is exposed in an array of patches each approximately equal in area to the correlation zone of the system. The image-correlation system is used to locate the surface of the terrain in model space and this information is used to place each patch of the orthophotograph in its appropriate position.

An image-registration system may perform an additional function in printing an orthophoto by electronic image transfer. This function is the transformation of the image as printed in such a manner that an orthographic projection is produced within the patch or slit. Where optical image transfer is used, a first-degree transformation may be accomplished by means of controllable anamorphic lenses.

It may be inferred from the foregoing that the printing patch or slit should not be larger than the correlation zone. It follows, therefore, that the use of a larger correlation zone permits the transformation of a larger area which in turn permits the use of larger patch or slit thereby reducing printing time.

The slit method of printing orthophotos is subject to dynamic errors that place an upper bound on the traversing velocity of the slit. These dynamic errors are caused by the inertia and flexibility of the moving parts of the plotter. Computer-controlled plotters may have an additional dynamic error caused by computional delay.

The patch method of printing avoids dynamic errors because all motion and computations cease before each patch is printed. The method has proven to be quite well suited to computer-controlled instruments as only one computation need be made per patch.

It would seem that continuous printing methods are more appropriate for systems having a small correlation zone whereas systems employing a relatively large correlation zone are more efficiently served by the patch method of printing. In continuous printing methods the correlator must be capable of responding quite rapidly to follow the terrain profile. Possibly a complex transformation system would be able to respond quickly enough to keep a fast-moving scanning slit on the terrain surface. However, this has not been achieved to date. Assuming that a large correlation zone area implies a complex transformation capability, the patch-printing method could allow sufficient time for correlation and transformation to take place before printing and moving on to the next patch.

Regardless of the printing method employed, experience has shown that the speed of orthophoto production is governed by the area of the correlation zone. The search for higher speed is in effect a search for means of enlarging the correlation zone.

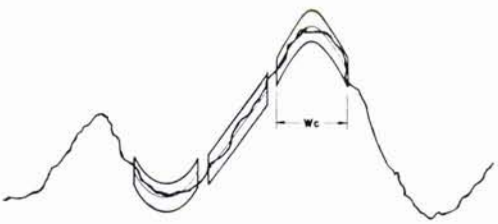

FIG. 8. Correlation zone with first- and second-degree transformation capability in rough terrain.

CORRELATION ZONE: AREA LIMITATIONS

Let us repeat the definition of the correlation zone. The correlation zone is the area of the images under correlation at any instant. The correlation zone (Figure 3) has a width W_c in x (and of course, a corresponding dimension in y not depicted) and a depth a called the correlation range. The portion of the terrain falling within the correlation range has a width b which delivers a useful parallax signal. Areas outside b give nonsense signals. The problem of improving correlation is the problem of extending the width of b to be equal or close to the entire correlation zone W_c.

We will now examine the problem of increasing the useful area of the correlation zone in automatic stereo image registration systems.

Figure 8 illustrates the effect of adding a second-degree polynomial transformation capability to a first-order system under a variety of terrain conditions. It may be seen from this figure that a second-degree transformation provides a parabolic curvature in model space and allows a considerably larger fraction of the correlation zone to be effective. Second-order transformation allows the use of a larger slit or patch for orthophoto printing. This is due to the improved edge matching of the strips or patches. Unfortunately, second-order polynomial capability requires the handling of three additional coefficients, each requiring a separate correlator section and memory section.

Higher-degree transformations allow a still larger effective correlation zone but require the addition of many more correlators and memories for the additional coefficients. The additional correlation capacity significantly cuts down the speed of operation of higher

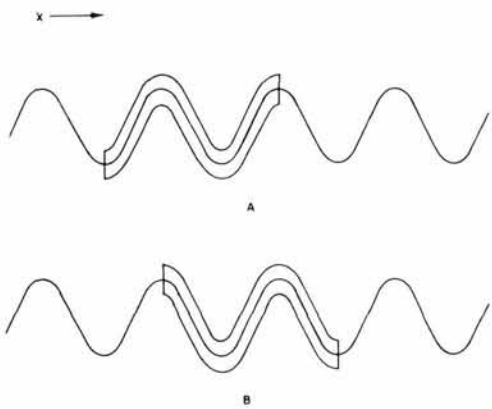

FIG. 9. Third-degree polynomial transformations.

degree transformation systems. Figure 9, Part A, illustrates a third-degree polynomial transformation applied to a correlation zone on the terrain having a third order requirement. In Part B, the correlation zone has been traversed in X a distance approximately one third of the zone's width. It can be seen that the coefficient for x^3 has reversed its sign. In general, higher-order coefficients must be capable of changing very rapidly in a continuously printing system. Unfortunately, these rapid changes are very difficult to attain and, as speed is essential, we reach an impasse.

At Hobrough Limited we have found the Δh matrix transformation to be a more practical approach. We have developed a method of providing a matrix transformation corresponding to a 50th-order polynomial. The matrix provides transformation of a stationary correlation zone of a much larger size than is possible with moving slit printing methods.

The effective correlation zone size completely depends on the transformation capability of the correlator. The larger the zone requirement, the more complex the transformation. We have found that transformation capability requires a memory of terrain form to store either the polynomial coefficients or the Δh values. The more complex the transformation requirement, the larger terrain form memory is required.

COHERENT LIGHT METHODS

The discussion so far has been confined to electronic correlation methods. Another technique is of interest to many of us: image correlation using coherent light has recently become feasible and research on its application to the automation of photogrammetry is now proceeding at the Bendix Research Laboratories in the United States. The coherent-light processing of images is a highly parallel method. In fact, the correlation zone may include the entire model area. Therefore, the method should be capable of speeds far in excess of electronic methods. Research has been directed toward automatic profile and contour printing but, theoretically, coherent-light methods could be used to expose orthophotos also. Such a technique may become competitive with electronic methods in the future.

In our opinion the difficulty with the coherent-light method lies not in correlation or parallax sensing, but in setting up a controlled transformation capability. Until such transformation can be achieved, it seems that correlation zones must be small and the available speed remain lower than with electronic methods.

We are not qualified however to evaluate coherent light methods in detail and would refer those interested to the literature published by the Bendix Corp.

SUMMARY

This concludes the technical discussion of automatic image correlation. Speed is the essence of economy, and we have endeavored to show that the speed of automatic compilation is controlled or limited in the following sequence:

1. To achieve high speed we must use a large correlation zone.
2. To use a large-correlation zone all the terrain must fall within the correlation range.
3. To achieve a wide correlation range a correlator must have a considerable transformation capability.
4. A complex transformation requires a voluminous terrain-form memory.
5. It is the speed with which one can accomplish the transformation and terrain form memory functions that sets the limiting speed on any automatic correlator.

We have shown how the limitations of the polynomial representation of terrain form led us to develop the Δh matrix representation which allows a greatly increased area of correlation zone and consequently a tremendous increase in the speed of automatic compilation. The next portion of this paper will describe an instrument which utilizes such transformations capability.

GESTALT PHOTO MAPPER SYSTEM

In our introductory remarks we stated that the attainment of speed in compilation was an economic goal. At Hobrough Limited we have been pursuing that goal and we will now describe a machine we have developed. The

GESTALT Photo Mapper is our solution to the problem of attaining an economical compilation speed.

Let us consider the GESTALT Photo Mapper with respect to some of the discussion in the first portion of the paper. A significant departure from previous orthophoto printers is that we have adopted the *patch* method in preference to the moving slit method of printing. We have developed a novel method of sensing Y-parallax which allows us to utilize a TV raster for correlation and printing. The size of printing patch is approximately 48 square millimeters defined by a mask in the printing optics. The correlation zone is slightly larger than the printing patch. A 3000-element Δh matrix representation is used to attain a high degree of transformation capability; in fact, the equivalent of a 50th-order polynomial representation.

In operation, all transport systems come to rest before the printing of each patch. After each exposure the computer directs the printer to move the sensitized film to the next patch position and the scanner to move the diapositives to the corresponding photo coordinates. When the correlator determines that the correct locations have been attained by the left and right diapositive plates in the scanner, it transforms the scanned patch into an orthogonal projection. As soon as the transformation is complete the computer signals the printer to expose the patch.

It is of interest that stereoscopic viewing is not used in the GESTALT Photo Mapper. The operator is supplied with a high resolution TV monitor for viewing the images. Either the left or right image may be observed on command. Normally the monitor alternates between images at a rate of four cycles per second. Thus, a parallax appears as a vibration of the image. Parallaxes within the entire correlation zone are cleared by the correlator, however, and the operator is required only to put the reference mark on the point of interest which appears stationary despite the alternating of the view from left to right.

GESTALT PHOTO MAPPER—PHYSICAL DESCRIPTION

The GESTALT Photo Mapper is a relatively small plotting instrument consisting of four separate sections or modules plus a preparation station. The Frontispiece is a sketch of the four modules. The scanning module (left) contains a glass deck upon which two diapositive transport systems are mounted. The diapositives are positioned by means of precision racks and pinions which maintain

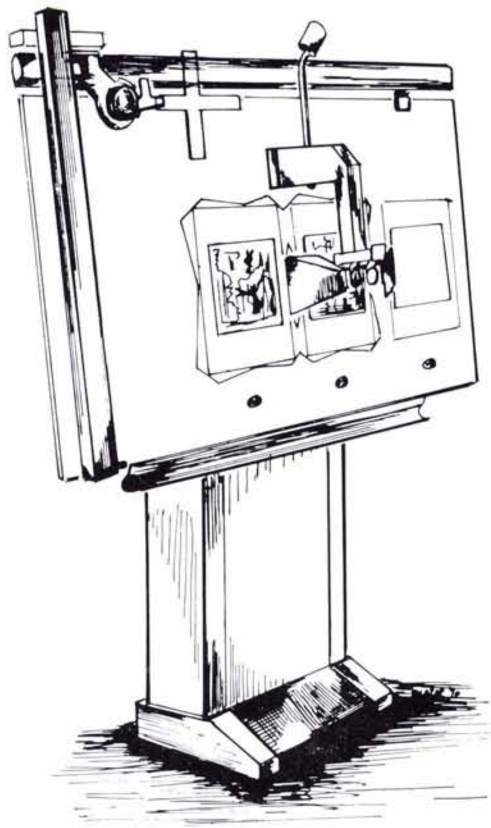

FIG. 10. The preparation station.

the Abbé condition in three dimensions. The correlator module (center) contains the correlator and its associated power supplies. In later instruments the correlator will be integrated into the control console (right of center). The present console contains a TV monitor, control electronics, a Nova computer. Teletype and steering controls for communicating with the computer are attached to the console. The printing module is located in a photographic darkroom and is similar in construction to the scanning module (shown in the Frontispiece on the far right).

OPERATIONAL PROCEDURE

Figure 10 is a sketch of the preparation station. The preparer is the most highly skilled (photogrammetrically) member of the operating team. He identifies the location of control and orientation points to an accuracy of about ± 2 mm on paper prints of each model.

To compile a model, the instrument operator starts the computer that immediately takes control of the system. Thereafter the computer is in communication with the operator by means of the teletype in conversational mode. The computer asks for data or decisions as it requires them.

For interior and absolute orientation the computer drives the left and right diapositives to the approximate locations of the various fiducial marks and control points, and the operator sets his reference mark on each. Relative orientation is conducted by the computer using the pre-selected areas without further assistance. Elapsed time from starting the computer to completing the orientation is about six minutes.

The printing sequence requires from 5 to 12 minutes. During this period between 600 and 1000 individual patches will be correlated and printed.

SUMMARY

This concludes our description of the function and operation of the GESTALT Photo Mapper system as it currently stands. The present instrument has been designed as an automatic orthophoto printer only. There is no provision for manual plotting. Through the use of modern integrated circuits we have been able to keep the size of the machine to a minimum. Throughout the GPM system we apply the principles developed at Hobrough Limited as outlined in the first part of this paper. The result of this application is that the speed of automatic compilation is adequate to provide a substantial economic advantage over manual methods for the first time.

CONCLUSION

Let us say a few words in final summation of this paper. The point which we have tried to convey to you is that to attain the high speed required to make automation an economic proposition, one must develop extremely complex stereo correlators with detailed terrain form memory. We have outlined the difficulties which beset the first generations of automatons for the past 20 years, and have outlined the solutions we have developed. Experience has shown that zero-order transformation systems are ineffective for image correlation. It is true that first-order transformation is effective, but also that terrain-form is more complex in large areas. Second-degree and higher transformations to a polynomial representation are too slow in themselves to allow for a useful over-all compilation speed. Because of the slowness of polynomial representation of terrain form we have developed the Δh matrix representation which in turn gives us a large correlation zone and a large printing area. However, the proof of the pudding is in the eating. Therefore we have outlined the operation and performance of the GESTALT Photo Mapper which we believe has attained the speed and accuracy required to take automatic stereo compilation out of the laboratories and government mapping agencies and into the world of daily work.

ASP Needs Old Magazines

Because of an unexpected demand for journals and student requests, the supply of some back issues of PHOTOGRAMMETRIC ENGINEERING has been depleted. Consequently, until further notice, National Headquarters will pay to the Regions—or to individual members—$1.00 for each usable copy of the following issues sent to Headquarters, 105 N. Virginia Ave., Falls Church, Va. 22046:

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1948	1, 2, 3	1964	1
1949	1, 4	1965	1, 2
1950	1, 2	1966	1, 5, 6
1951	1, 2, 5	1969	1, 7
1952	1, 2, 3	1971	1