APPLICATION OF HYBRID ANALOG AND DIGITAL TECHNIQUES
IN THE
AUTOMATIC MAP COMPILATION SYSTEM

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SUMMARY

The Automatic Map Compilation System, developed and operating at Thompson Ramo Wooldridge, abstracts terrain altitude information from aerial photographs by correlating the imagery appearing on stereo pairs, and outputs contour information and new photographs in which the imagery appears in “true” orthographic projection position. The system uses a small digital computer to control analog elements that provide access to the photographic store and process the resulting signals to measure the altitude errors; the errors are then provided as an input to the computer. The system operates through a set of continuous profiling operations to cover the stereo area.

Since the input for the map compilation is in analog form as pairs of photographs, some precision analog equipment is required for the processing. The solution described avoids transferring the information to a digital store, and thus tremendously simplifies the storage and data handling problem. In effect, the integration of the computer with the analog elements produces a special purpose computer that is extremely efficient for the application. The system represents a solution to a problem which until recently was believed to lie exclusively within the domain of human sensory functions, viz., the precision mechanization of stereo perception for the purpose of measuring altitudes from aerial photographs.

INTRODUCTION

The Automatic Map Compilation System developed at Thompson Ramo Wooldridge under the auspices of the U.S. Army Engineer Geodesy, Intelligence and Mapping Research and Development Agency correlates the imagery appearing on stereo pairs of aerial photographs and outputs a chart showing the altitude contour intervals over the stereo area and a new photograph in which the imagery has been moved so as to appear in correct orthographic projection position to a selected scale. The system utilizes a combination of digital and analog techniques to achieve the required accuracy and speed of operation. In effect, a small digital computer is integrated with an analog memory and other peripheral equipment to obtain a very effective special purpose computer.

The input data for a given compilation is in the form of a pair of aerial photographic transparencies together with pertinent camera data; i.e., position and attitude of camera for each transparency, focal length of camera and distortion characteristics of the lens. The amount of detail information available in the photo-
graphs and the nature of the access requirements makes it expedient to use the original photographs as the principal data store for the system.

The system therefore requires a digital computer being on-line with suitable scanning equipment to provide access to the photographic store. It is also convenient to process the photographic data external to the computer and to store the desired output information on new photographs prepared by the equipment. The process then reduces to one in which the digital computer provides precise control information to the analog system with the analog system providing feedback in the form of measured errors which then serves to keep the computer functioning in response to the photographic store.

DEVELOPMENT OF HEIGHT-ERROR SIGNALS FROM STEREO PAIRS

The development of a height-error signal, the key to automatic map compilation, can be seen by reference to Figure 1. Two camera stations C and C' are shown together with an object point P on the surface and its images p and p' in the film plane for the two camera positions. Suppose that the point P was, in some manner, estimated to be at P_e, i.e., below its correct position. One would then be led to look for p and p' by scans s and s' centered on the two representations of P_e; it is obvious that p appears to the left of center and p' to the right of center in these two scans. If P_e had been estimated too high instead of too low, then p would appear to the right of center and p' to the left of center in the two scans. Since P is an arbitrary point in the stereo field, its location in a scan is meaningless. Of extreme significance, however, is a comparison of the position of corresponding imagery within the two scans. If the altitude selected is correct, corresponding imagery will appear at the same positions in the two scans, while if there is any altitude error it will show up as a proportionate shift in the positions in the two scans. A measurement of this shift is, therefore, equivalent to a direct measurement of the error in the estimate of altitude. It is of interest to note that the camera separation B is made large—of the order of the altitude—to exaggerate the shifting of the images with altitude changes.

In the Automatic Map Compilation System, flying-spot scanners are used to obtain signals from areas estimated to be centered on the same point on the surface. If, as shown in Figure 1, scanning proceeds from left to right a low estimate of altitude will yield signals in which elements from C are ahead in time of corresponding elements from C'; for a high height estimate, the reverse is true. Correlation circuitry, described below, is used to match corresponding signal components and to provide an appropriate output to the related control elements.

SYSTEM DESCRIPTION

The photographs to be compiled, in the form of positive transparencies, are mounted together with a photosensitive film sheet on a common carriage, as shown in Figure 2. The carriage is mounted on precision ways, and arrangements made to communicate its position to the computer. For the purpose of the compilation, a rectangular system of coordinates is used with the origin centered at one camera.
station and the Z axis passing through the second camera station extending vertically upwards. These are related to carriage coordinates through the desired scale factor; i.e., 
\( x_0 = X/m \) and \( y_0 = Y/m \) while \( z_0 = Z/m \) is used in the computer program. This coordinate system permits a common \( y_0 \) value and \( x_0 \) and \( z_0 \) values that are simply displaced by the corresponding camera station separation components.

In this system of coordinates, the position of a given terrain point as it appears on the two photographs (assuming a distortionless lens) may be expressed by the relations

\[
x = \frac{U_1 X + U_2 Y}{W_1 X + W_2 Y + Z} \quad (1a)
\]
\[
y = \frac{V_1 X + V_2 Y}{W_1 X + W_2 Y + Z} \quad (1b)
\]

and, for the second photograph

\[
x' = \frac{U_1'(X - B) + U_2'Y}{W_1'(X - B) + W_2'Y + (Z - \Delta Z)} \quad (1c)
\]
\[
y' = \frac{V_1'(X - B) + V_2'Y}{W_1'(X - B) + W_2'Y + (Z - \Delta Z)} \quad (1d)
\]

Equations (1) are in normalized form; the origin of coordinates in the photographs is taken to be the nadir point, the point where the vertical through the center of the lens passes through the film (and hence where the image of the point directly beneath the camera appears). The origin of coordinates of the field of view, i.e., of the \((X, Y, Z)\) system, is taken to be at the position of the lens for the first photograph; the displacement \(B\) of the \(X\) coordinate, and \(\Delta Z\) of the height coordinate for the second photograph represent the change in position of the camera station for the two photographs.

Equations (1) permit the calculation of the coordinates on each of the photographs where a given spatial point \((X, Y, Z)\) is to be found. In general, the positions \((x, y)\) and \((x', y')\) will not agree with the table position \((x_0, y_0)\); the system permits the observation of the offset position through the use of a flying-spot scanner with an associated imaging lens whose position is under the control of the computer. The imaging system is shown in Figure 3. The flying-spot scanner is shown positioned over a point \((x_0, y_0)\) with the lens displaced by \((x_1, y_1)\) so that a centered spot would be imaged at a desired position \((x, y)\).

Four flying-spot scanners are used—one with each photograph and two for data printout. The latter are used with fixed lens so that the data is printed out at the position \((x_0, y_0)\); i.e., at the properly scaled map coordinates of the area under observation at a given time. Data printout takes two forms: (1) An altitude chart exposed by computer control of the brightness of one scanner in accordance with the measured altitude; three brightness levels are used in a rotary sequence to show successive contour intervals; (2) A new photograph exposed by reproducing the image picked up by one of the photograph scanners and imaging it appropriately on the photosensitive film sheet.

During the setup operation, the photographs are mounted so that their axes agree closely with the machine axes. The computer then directs the system to move to the position of a point which can be identified easily and whose photographic coordinates are accurately known. The operator observes the scanned area as reproduced on a stereoviewer, basically a twin TV system having an electronically generated crosshair. Through Flexowriter control of the computer, the operator moves the lenses until the required point on the scanned area is centered on the crosshair; when this has been accomplished, the computer records the position of the point in system coordinates and then moves the scanned area to a second point where the operation is repeated. Once this has been accomplished, the computer modifies the coeffi-
cients of equations (1) (including a shift of the origin) and commands the system to move to a third “check” point as defined by spatial coordinates \((X, Y, Z)\) so that the modified equations (1) are used. If the check point is well centered in the crosshairs, it is assumed that the correct relationships have been entered into the computer and the compilation process is started.

The compilation operation consists of a series of profiling runs in each of which \(x_o\) is constant and \(y_o\) proceeds in 0.010 in. steps. At each step, with \(x_o\) and \(y_o\) defined and an estimate of altitude available from previous measurements, the computer performs the arithmetic indicated by equations (1), subtracts \(x_o\) or \(y_o\) to obtain the required offset to locate the estimated point on the two photographs and outputs the resulting four values to corresponding digital-to-analog converters. The computer also outputs a signal corresponding to the altitude of the camera above the point under consideration and a signal to control the printing of the altitude chart. The analog system then takes over while the digital system proceeds to update the information for the next measurement point.

The rasters of the flying-spot scanners are centered on the designated areas by the servos acting in response to the corresponding d/a outputs. In addition, the rasters are individually controlled in shape and size so as to scan the photographs in one-to-one correspondence with the instantaneous position of the printout scanner exposing the new orthographic projection photograph. The process is best explained by the pertinent mathematics: let equations (1a) and (1b) be rewritten in the form

\[
x = F(x_o, y_o, z_o) \quad (2a)
\]

\[
y = G(x_o, y_o, z_o) \quad (2b)
\]

If the nominal orthophoto position \((x_o, y_o)\) is varied by \((dx_o, dy_o)\) the corresponding changes in \(x\) and \(y\) are given by

\[
dx = \left(\frac{\partial F}{\partial x_o} + \frac{\partial F}{\partial z_o} \frac{\partial z_o}{\partial x_o} \right) dx_o + \left(\frac{\partial F}{\partial y_o} + \frac{\partial F}{\partial z_o} \frac{\partial z_o}{\partial y_o} \right) dy_o \quad (3a)
\]

and

\[
dy = \left(\frac{\partial G}{\partial x_o} + \frac{\partial G}{\partial z_o} \frac{\partial z_o}{\partial x_o} \right) dx_o + \left(\frac{\partial G}{\partial y_o} + \frac{\partial G}{\partial z_o} \frac{\partial z_o}{\partial y_o} \right) dy_o \quad (3b)
\]

In equations (3) \(dx_o\) is implemented as a fast (line) scan and \(dy_o\) as a slow (frame) scan. For the second photograph \(F\) and \(G\) are replaced by \(F’\) and \(G’\). The current implementation includes only the scaling terms \(\partial F/\partial x_o\) and \(\partial G/\partial y_o\) as obtained by a low accuracy \(d/a\) from the computer. It has been demonstrated that an appropriate error signal for use in implementing the terrain slope terms \(\partial z_o/\partial x_o\) and \(\partial z_o/\partial y_o\) can be obtained by the analog system by comparing the altitude error signals on appropriate halves of the scan. It is anticipated that the scan equations will be more completely approximated in the near future with the remainder of the partials required to implement the scan equations (3) obtained from the computer.

With the two photographs examined at nearly corresponding areas and with the scanning proceeding along lines that are effectively in the direction of the camera separation, it is possible to use straightforward analog correlators to detect any height error as evidenced by a time delay of corresponding elements in the pair of video signals.

The height-error measuring unit is diagrammed in Figure 4. It consists of the correlation circuitry which yields the height-error signal, an integrator, a \(\pm\) threshold detector, a reversible counter and an associated \(d/a\) converter providing an appropriate \(x\) deflection voltage to the photograph scanners. At the beginning of a measuring cycle, a pulse from the computer sets both the counter and the integrator to zero. As the scan progresses, if
there is any error the integrator output will increase until the threshold is exceeded. This causes the reversible counter to step in the appropriate direction and the integrator to be reset to zero so that an independent error evaluation can again be made.

The count operates through the d/a converter to shift the photograph scan in a direction to compensate for the observed error. As the scan continues, any uncompensated error will cause further stepping of the counter until equilibrium is reached. At an appropriate point in the computational cycle, the measured height error is transferred into the computer and added to the original height estimate to correct the value in the computer memory. The cycle is then repeated for the next point in the profiling sequence.

As the photographs are scanned the resulting video information is used to recreate the photographic element on the scanner used to expose the new photograph. In practice the original height estimate is sufficiently close to, insure adequate accuracy in the resulting photograph. A height signal, in the form of one of a set of three brightness levels, is obtained from the computer and used to control a fourth scanner exposing the altitude chart. An orthophoto and corresponding altitude chart made by the equipment are shown in Figure 5. A photograph of the basic mechanical assembly for the system is shown in Figure 6.
The description of the system given above omitted many interesting details. Some of these will now be described.

COMPUTER PROGRAM

The timing problem for the computer program for a Y profiling operation is shown in Figure 7. It consists basically of three phases:

PHASE 1—Initiated by reading the altitude correction signal and followed by the computer preparing the new photograph position output command;

PHASE 2—The analog system operates to evaluate the height error while the computer prepares the data to expedite the Phase 1 operation;

PHASE 3—A waiting period for the analog system to move to a new position. The table position is read periodically during this period and the next cycle is initiated immediately on the signal indicating that a new position has been reached.

During the first phase the altitude error, measured at the last position, is added into the previously prepared denominators of equations (1), and these are divided into the previously prepared numerators. The quotients are then added to a constant term and the result outputted through the digital-to-analog converters to the analog system. The analog system is idle during this period, so the time is made as short as possible.

The major part of the calculations are made in the second phase. The operation begins with the calculation of the output for the altitude chart. This is accomplished by assigning the current altitude to one of three levels in a rotary sequence. The result is outputted to the analog system where it is used to set the brightness of the altitude chart printout scanner. (Since the printout is made one cycle late, the analog printout is displaced one element ahead to compensate.) The numerators and denominators of equations (1) are then updated for the next cycle by adding a constant to each appropriate to the $y_0$ increment being used (0.010 in.). The computer then calculates the position code for the next expected position (a two bit Gray code is used). This is then followed by one of a group of calculations that are rotated among six cycles, since they change very slowly compared to the accuracy requirement. Included here are corrections for distortion in the photography and the scale required by the analog system for scan adjustment.

When a profile has been completed the carriage is moved over the desired amount in $x_0$ and the numerators and denominators of equations (1) incremented a corresponding amount. The commands to increment the terms during the $y$ profiling operation are then reversed in sign and the $y$ motion started in the opposite direction.

STOP-MOTION SYSTEM

The speed requirement for the system is such as to make the design of a mechanical carriage that stops at each measurement point impractical, while the accuracy requirement demands
that measurements be made about well-defined positions in the photographs. These seemingly incompatible requirements are satisfied through the stop-motion element.

The stop-motion circuitry develops a pair of sawtooth voltages, as shown in Figure 8. These are triggered by alternate Gray code changes and have slopes that are dependent on the rate of motion of the carriage. If either of these, say A, is supplied to the flying-spot scanners, the result is to make the movement of the spot such that its image on the photograph appears stationary. The sawtooth voltage persists for two Gray code intervals—0.020 in.—and then shifts to permit a new area 0.020 in. behind to be examined.

In steady state operation, the output is switched between the two voltages A and B by computer command. Successful operation requires that each computer operating cycle take less time than the interval between Gray code changes. A given computer cycle might, for example, be completed at point C; the computer would then stall until the next Gray code change before providing the signal to switch to the alternate sawtooth. Thus, the two signals can be adjusted dynamically, independently of the computer, without danger that operation with the computer will change the calibration.

SERVO COMPENSATION

The speed requirements for the system also pose a problem for the rapid positioning of the scans to the required positions on the photographs. The displacement of the scans from orthophoto position is so large that it is not practical to use a completely electronic scan positioning system. As described earlier, and shown in Figure 3, primary positioning is accomplished using a pair of servo systems to position the lenses. The response of such servos operating by themselves is too sluggish to operate effectively in this application. For this reason the servo error signals are supplied to their respective scanners to compensate for any instantaneous error. Thus immediately after the computer outputs a new position command through the d/a, the system can start accumulating a meaningful error signal since the scan is centered on the desired areas.

The basic correlator used in the system is essentially a quarter-square multiplier. The configuration is shown in Figure 9. Operation is as follows:

Assume the diodes shown operate as square law devices for signals of appropriate polarity. The two transformers are arranged to supply various combinations of the two input voltages A and B to the four diodes. If the output of a diode is expressible by \( i = Ke^e \), where \( e \) is the input voltage and \( i \) the output current, then for the four diodes the sum is

\[
i = K[(A + B)^2 + (-A - B)^2 - (A - B)^2 - (-A + B)^2] = 4KAB
\]

so that the output is proportional to the instantaneous product of the two input signals. (Deviations of the diodes from square law does not significantly affect operation of the circuit as a correlator.) The integrated output, obtained from the capacitor, is then used as a measure of the correlation of the two input signals.

Two correlators are used in the height sensing circuitry along with a pair of delay lines, as shown in Figure 10. The figure illustrates the operation where the signal from the first photomultiplier is ahead of the signal from the second. For this condition Correlator 1 receives signals that are nearly coincident in time, and it therefore has a large output. Correlator 2, however, receives signals that are displaced in time so that it has a low output. The differencing network produces a corresponding output.
If the signals are coincident in time, the difference goes to zero, while if the direction of the differential reverses, the output reverses in polarity. The output is therefore appropriate to drive the integrator of the height-error measuring unit shown in Figure 4.

SLOPE COMPENSATION CIRCUITRY

Implementation of the photograph scanning signals described by equations (3) is dependent upon the derivation of suitable slope error signals (an early implementation used the computer to define the slopes, but the data for this is too noisy). The slope error signals have been derived from circuits analogous to the height-error sensor. The error in \( \frac{\partial z}{\partial x} \) is determined by time-gating the photomultiplier signals so that for the first half of an \( x \) scan the signals are applied to the output with one sign and for the second half with reversed sign. If there is a uniform altitude error over the scan, it will be cancelled between the two halves; however, if there is a height-error differential over the scan (a slope error), the output will be appropriate to drive the slope error store to correct the slope in the system. Similarly, any error in \( \frac{\partial z}{\partial y} \) is determined by time-gating the signal at the middle of the \( y \) scan.

CONCLUSION

The problem of automatically reducing stereo pairs of aerial photographs to contour intervals and orthophotos as a step in map making involves the manipulation of a large amount of data. The solution described retains the original photographs as the principal store for the process, thus avoiding the necessity of shifting data around in a digital store of hundreds of megabits.

Appropriate scanning equipment provides rapid access to the photographic store as needed, and straightforward analog techniques permit the processing of this information external to the computer so that the computer operation can be largely limited to those requiring accuracies not readily achievable in the analog system. Since the computer is in the system, it is expedient to use it for some low accuracy calculations that would otherwise unduly complicate the analog system—for example, the correction of distortion in the photography is made in the digital computer. It is believed that the system configuration represents a nearly optimum marriage of digital and analog techniques for the application.

A prototype of the Map Compilation System makes about fifty independent altitude measurements per second to an accuracy of better than one one-thousandth of the flying altitude. It has compiled a stereo pair in about an hour and a half, with very little assistance from the operator. A corresponding hand compilation would take much longer, and, in complex areas, would probably miss some information. The present system has adequately demonstrated the feasibility of automatic compilation. A second generation instrument is now contemplated that will be faster, more accurate, and more versatile. It will follow closely the operation of the present system.

ACKNOWLEDGEMENT

Achievement of a working system required a team effort. The contributions of George Miller, mechanical engineer, Glen Kimball in electronic design, and Jules Mersel in computer programming were particularly significant.

BIBLIOGRAPHY