*Systems Design of a Digital Control Computer for an Analytical Stereoplotter**

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ABSTRACT: *The analytical stereoplotter is a new type of photogrammetric plotting instrument which is based on analytical rather than simulation techniques. In this concept, the two photographs of a stereo pair are moved differentially in a horizontal plane so as to synthesize the more general motions which take place in conventional mapping instruments. Such differential movements are controlled by a computer in accordance with the position of the point of of interest in the stereo model. In the process, the computer introduces corrections for such factors as earth curvature, atmospheric refraction, and lens distortion.*

In a digital computer designed for this application, the major real-time calculations are handled on an incremental basis using digital-differential-analyzer techniques. Auxiliary calculations, such as those involved in the set-up or orientation procedures, are handled by means of whole-number, or general-purpose techniques.

The incremental section of the computer contains 160 integrators, each of which is processed 100 times per second. On each iteration, up to 64 basic increments can be assimilated as either dependent or independent variable inputs. The computer is fully transistorized and employs magnetostrictive delay lines for storage.

THE ANALYTICAL PRINCIPLE

PHOTOGRAMMETRIC plotting instruments currently in use depend in general on a complete physical simulation of the geometry involved in the original photographic situation. Such simulation is accomplished by providing mechanically the large number of degrees of freedom permissible in the original situation, and by providing an optical system appropriately related to the optics of the taking cameras. Thus the instrument is relatively complex mechanically and its optical system may have to be selected according to the cameras employed.

A new principle for photogrammetric plotters, developed and reported by Helava, makes extensive use of electronic computing and control techniques (ref. 1). The Helava concept in effect employs analytical methods rather than physical simulation in order to reconstruct the stereo model. As a result, the mechanical structure of the plotter is simplified considerably, and the optical system need not be related to the optics of the original cameras.

Because of these and other factors, the instrument can accommodate a wider range of photographic situations and its versatility is increased generally. Initial set-up time can be reduced appreciably by the incorporation of computational features which assist in the orientation procedures. Also, the instrument can more directly take advantage of any data which may already be available in numerical form, such as camera coordinates or ground control coordinates.

Better accuracy can be expected, both because of the mechanical simplification, and because the plotter computer can more completely compensate for such non-idealities as earth curvature, atmospheric refraction, lens distortion, film shrinkage, and systematic instrument inaccuracies. If desired, mapping transformations can also be accomplished in the plotting process. Finally, the analytical approach appears to have greater potential for automation in its adaptability to electronic stereo perception techniques, and its ability to produce compact, machine-readable records for subsequent steps in the map-

* Presented at the Society's 27th Annual Meeting, The Shoreham Hotel, Washington, D. C., March 19–22, 1961.

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making or data-reduction process.

A plotter of this type, designated the AP/1, is currently under development by OMI† and Bendix.‡ The mechanical and optical components of the system are being designed by OMI, and the associated computer is being developed for OMI by the Bendix Corporation. This paper is concerned primarily with the computer. It first reviews briefly the overall concept of the instrument and the AP/1 in particular, then discusses the functional requirements of the computer, and finally describes the specific approach being taken in the implementation of the computer and its relationship to automatic stereo perception techniques.

OVERALL SYSTEM CONCEPT

Figure 1 illustrates schematically the system concept as a whole. In the center of the diagram is the main optical and mechanical assembly, whose function is to provide the proper relative motion between an optical viewing system and the two photographs of a stereo pair.

In the mechanical configuration suggested herein, the two photographs are mounted on separate carriages, with the motions Δx_1 and Δy_1 for photo 1, and Δx_2 and Δy_2 for photo.§ The photo carriages, in turn, are mounted on a main carriage which moves in the directions X and Y in response to handwheel motions introduced manually by the operator. The quantities X and Y represent the point of interest in the stereo model and are thus transmitted in suitable form to the coordinatograph for plotting.

The X and Y signals are transmitted to the computer also, along with the desired elevation E as established by the foot control. With this information, the computer generates command signals for the Δx and Δy motions of the two photo carriages. These motions, which are superimposed on the common main-carriage motion, are controlled in such a way as to maintain a properly fused three-dimensional image, with the floating mark at the elevation prescribed by the foot control.

In an ideal situation, the only differential motion required to keep the floating mark on the surface of the terrain would be in the x direction. The net amount of this motion would correspond to x parallax and would therefore be a measure of the elevation of the point of interest in the model.

In a practical case the situation is generally not this simple. Since the photographs are constrained to move in a single plane in this instrument configuration, both x and y motions may be required to compensate for any tilt of the camera at the time the photographs were taken. Likewise, both x and y motions are required in general to account for differences in camera height and focal-length and to correct for earth curvature, atmospheric refraction, lens distortion, and film shrinkage.

The function of the computer therefore is to accept as inputs X, Y, and E signals representing the desired coordinates as established by the handwheels and foot control. With this information, it must generate on a continuous basis the necessary Δx and Δy differential motion commands. In addition to this primary function, the computer must also

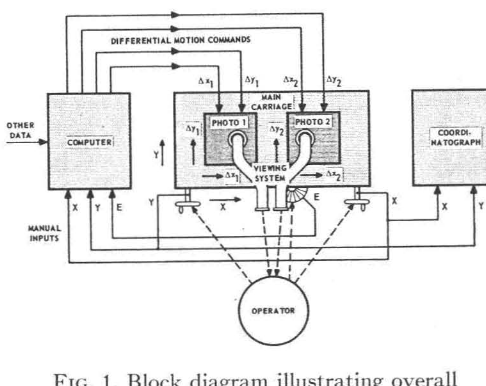

FIG. 1. Block diagram illustrating overall concept of the analytical plotter.

† Ottico Meccanica Italiana; Rome, Italy.

‡ This equipment is currently being manufactured for the Fairchild Camera and Instrument Corporation under prime contract with the U. S. Air Force Rome Air Development Center.

§ In this paper, lower case x and y are associated with photo-coordinates and photo-scale, and upper case letters (X, Y, Z, E) refer to the stereo model.

assist in establishing the correct interior, relative, and absolute orientation. For use in accomplishing these various tasks, the computer is supplied with other data as needed, such as lens characteristics, focal-lengths, and film-shrinkage coefficients.

The AP/1 Stereoplotter

Figure 2 shows an engineering mock-up of the main optical-mechanical assembly being developed by OMI for the AP/1 stereoplotter. In this photograph, the two photo carriages are visible in the area just under the open hood. The light sources are located above the carriages, and the optical viewing system is underneath. Operational controls are grouped on a large control panel between the operator's handwheels and the viewing optics. The large wheel in the center of the panel is associated with the Veltropolo $X-Y$ steering system. Most of the other controls are used only during the initial set-up and orientation procedures.

As a specific embodiment of the analytical principle, the AP/1 is functionally equivalent to the schematic shown in Figure 1. However, there are a number of differences in mechanical detail which simplify the structure of the machine still further.

For example, in the AP/1 configuration, the photo carriages move in the y direction only. Motion in the x direction is obtained by moving the viewing heads. Thus the relative motion required between each photo carriage and its viewing system is obtained without stacking one slide on top of another. Likewise, there is no main carriage as such. The common motion is introduced instead by coupling the X and Y handwheel motions into the individual photo-carriage lead screws by means of differential gears. If desired, the common motion can also be included by the computer in the commands generated for the photo carriages, thus eliminating the differential gears.

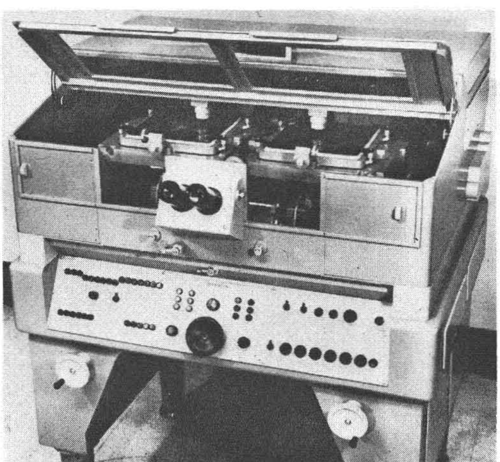

Fig. 2. Engineering mock-up of the AP/1 optical-mechanical assembly (constructed by OMI).

Overall accuracy of the instrument as a whole, including computer, is expected to be better than 10 microns rms, referred to photo-scale, at plotting speeds as high as 3 millimeters-per-second. In addition, the instrument is to be capable of slewing at 20 millimeters-per-second. The instrument is designed to handle standard 9-inch diapositives.

Functional Requirements of Computer

Figure 3 shows the geometry involved in the situation the computer must handle. There are five principal coordinate systems of interest. One is the so-called model coordinate system, X_m, Y_m, and Z_m, in which the point of interest is located in the three-dimensional image-space. These coordinates are closely related to the positions of the X, Y, and E hand and foot controls.

The next two coordinate systems are associated with the perspective centers of the two photographs. They are represented by the axes labelled X''', Y''', and Z''', with the subscript 1 or 2 to denote the photograph with which they are associated. In each case, the origin is located at the perspective center with the Z''' axis perpendicular to the photograph.

The last two coordinate systems are in the plane of the photographs and are represented by the x and y axes. These axes correspond to the directions in which the photo carriages can move physically.

For each point in the model, with coordinates X_m, Y_m, and Z_m, there is a corresponding point in each photograph. It is the function of the computer to determine the location of these points in photo coordinates so that they can be positioned to the center of their respective optical viewing systems.

In performing this function, the computer first determines the position of the model point in each of the X''', Y''', and Z''' coordinate systems. This process amounts simply to a coordinate transformation, consisting of a translation from the model center to the photograph perspective center, and then a series of three rotations, corresponding to the tip, tilt, and swing of the camera.

At this point, the computer has determined the direction of the ray from each perspective center to the model point of interest. It is

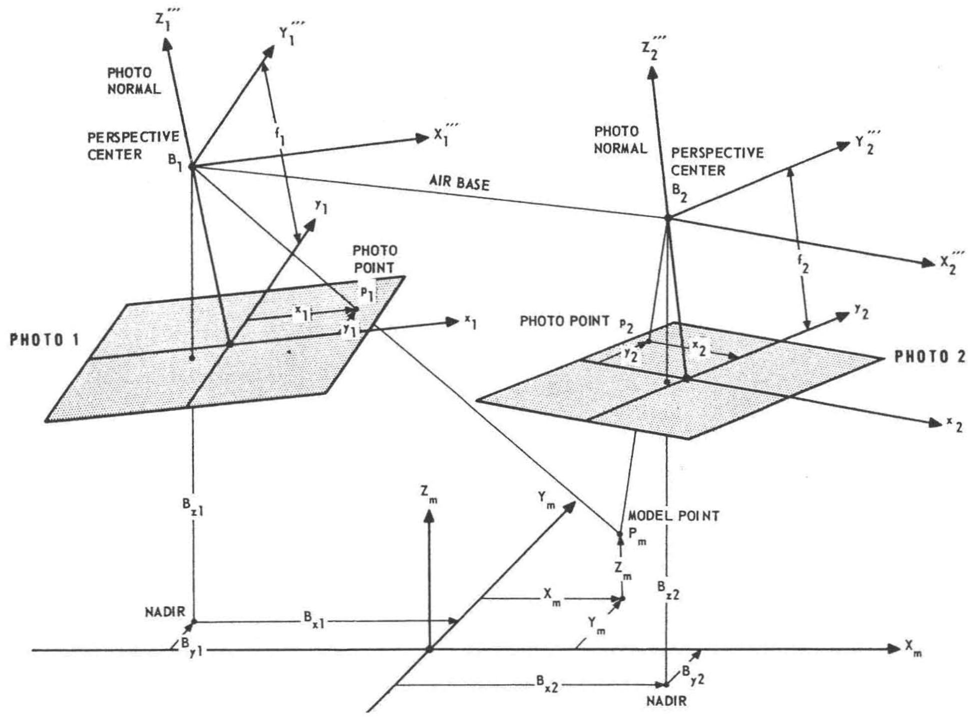

FIG. 3. Geometry and principal coordinate systems involved in the computation.

then only necessary to determine the point at which the rays intersect the planes representing the photographs. These planes are parallel to the X''' and Y''' axes and are displaced in the Z''' direction by the focal-length. Thus, x and y are proportional to X''' and Y''', respectively, with the same factor of proportionality which relates the focal-length f to Z'''.

Solution of the geometrical problem just described represents a major part of the computer's job—by far the most demanding portion from the viewpoint of accuracy and speed. There are a number of other computer functions, however, associated with the various corrections that must be applied. The manner in which these corrections are introduced is shown in Figure 4.

In this diagram, the top half is associated with photograph 1 and the bottom half with photograph 2. The two halves are essentially symmetrical about a horizontal line through the center. Referring to the top half, the blocks labelled "coordinate translation and rotation" and "location of point in plane of photo" perform the basic geometrical computation to locate the point in photo 1 corresponding to the model point, X_m, Y_m, and Z_{ml}.

The X_m and Y_m coordinates may be derived directly from the X and Y handwheel motions, which as indicated previously also drive the coordinatograph. In general, however, provision is made for introducing arbitrary additive corrections between the model coordinates and the plotting coordinates. In this way, corrections can be made for certain types of systematic errors in the system, or alternatively appropriate distortions can be introduced to accomplish certain types of mapping transformations.

The Z_{ml} model coordinate is closely related to the elevation input as derived from the foot control. However, the elevation input is first corrected for earth curvature. It is also convenient to account for atmospheric refraction by means of a small correction at this point. These two corrections are combined with the elevation signal in the block labelled "summation" to provide the Z_{ml} input for coordinate translation and rotation.

In general, the curvature correction depends on the X_m and Y_m coordinates of the model point and on the point of tangency with the sphere. The refraction correction depends on the X_m and Y_m coordinates, as well as on elevation, camera height, and nadir coordinates. For most situations, the nadir coordinates are generated within the computer, but camera height and point of tangency must be supplied externally. The same curvature correction applies to both photos, but in general the refraction corrections differ be-

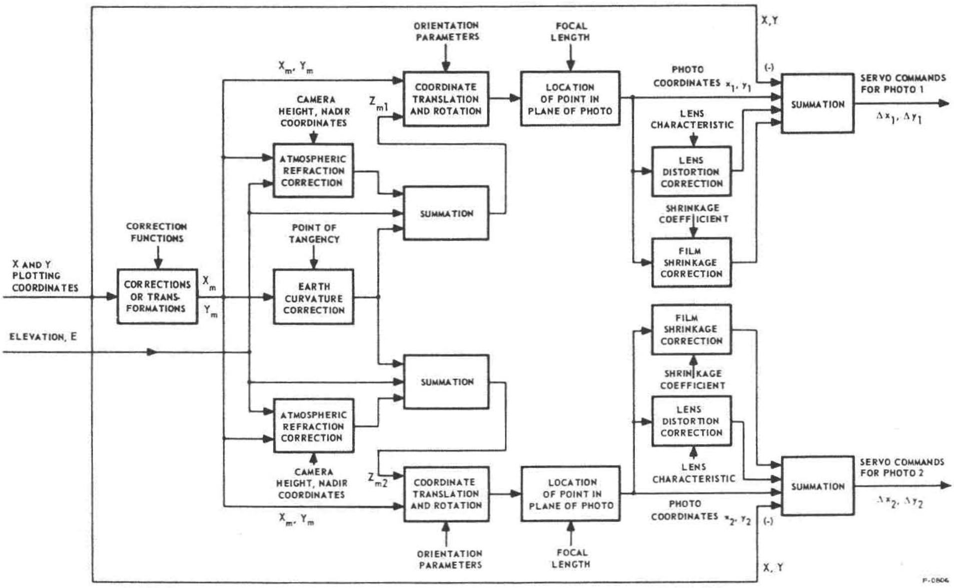

FIG. 4. Flow chart of main computations.

cause of differences in camera height and nadir point.

The coordinates x_1 and y_1 represent in effect the location of the model point with respect to the principal point of the photo. This information is sufficient to generate correction terms for the lens from a knowledge of the lens distortion characteristic. Likewise, from x_1 and y_1, a correction can be computed for film shrinkage.

With these two corrections applied to x_1 and y_1, the position of the point of interest in the photo is accurately known. This is the point that must be aligned with the center of the optical viewing system. Thus the corrected x_1 and y_1 represent the distances that photograph 1 must be moved with respect to its viewing optics.

In the instrument configuration shown in Figure 1, the photograph has already been moved the distances X and Y as a result of its position on the main carriage. The required differential motions, then, are the differences between the corrected x_1 and y_1 and the main carriage motions, X and Y. These differences are determined in the last block labelled "summation" and are used to control the servos positioning the photo carriage. In a machine configuration without the equivalent of a main carriage motion, the corrected x_1 and y_1 are suitable for controlling the photo-carriage motions directly.

COMPUTER DESIGN

The computations outlined above are all functions that must be handled on a real-time continuous basis during the operation of the plotter. For each new combination of X, Y, and E, new differences, Δx and Δy, must be computed. If the handwheels or the foot wheel are in continuous motion, the differences must be generated continuously and smoothly in order that the correct three-dimensional image will be presented to the operator at all times.

It is this real-time problem that is primarily responsible for determining the character of the computer. The significant factors here are the accuracy with which the photo positions must be computed, the plotting and slewing speeds that must be handled, and the smoothness or continuity required in the motions.

An indication of the required accuracy can be obtained from the relationship of the allowable overall system error of 10 microns rms to the size of the photographic plates being handled (approximately 240 millimeters). The ratio of these figures, 1 to 24,000, suggests an absolute lower bound on computer accuracy. An accuracy two to five times better would obviously be desirable. In accordance with the performance objectives of the instrument, this accuracy must be maintained at plotting speeds as high as 3 millimeters-per-second. Capability for slewing at speeds as high as 20 millimeters-per-second must be provided, but accuracy need not be maintained at these speeds.

These three factors—accuracy, speed, and continuity—together suggest the use of digital incremental, or *DDA*, computing techniques (ref 4). Analog techniques, al-

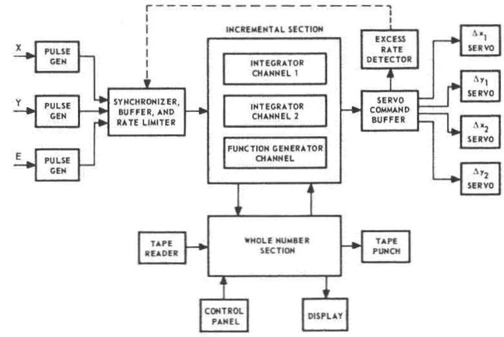

FIG. 5. Block diagram of computer.

though good from the viewpoint of speed and continuity, are marginal with regard to accuracy. Whole-number digital techniques, as employed in conventional general-purpose digital computers, are good as far as accuracy is concerned, but they are not able to provide efficiently the required conbination of speed and continuity. Incremental techniques, on the other hand, are relatively well-matched to the problem. Therefore, the incremental approach has been selected for the computer now under development to handle the main part of the problem.

For other portions of the problem, a whole-number, or general-purpose computer would be desirable. In addition to the real-time computations, for example, other calculations must be handled during the initial set-up of a pair of photos and during the read-in and read-out of data. Such calculations include the determination of the orientation parameters (kappa, phi, omega, and the air-base components). For many of these functions, incremental techniques do not represent an efficient solution. For these and other reasons, a whole-number section of modest performance is also included in the computer.

The AP/1 computer thus represents a combination of incremental and whole-number techniques. The incremental section provides the accuracy, speed, and continuity required for the real-time computation, and the whole-number section provides a high degree of versatility for the supplementary operations desirable in an automatic instrument of this type.

Figure 5 shows the general organization of the computer, including the relationship of the incremental and whole-number sections. The principal inputs to the incremental section come from quantizers, or pulse generators, coupled to the X and Y handwheels and the E foot control. The quantizers generate pulses at a level of 5 microns-per-pulse referred to model-scale. The pulses first pass through circuitry which synchronizes them with the internal clock of the computer. This circuitry also provides some buffering and rate limiting, in case the operator attempts to slew at rates higher than about 20 millimeters-per-second.

At the output end of the incremental section, the computer photo-carriage command pulses are distributed from the servo command buffer to the four servos. The servos in this case are of the phase-analog type, employing conventional two-phase synchros, or resolvers, for feedback. The command phase information for use in this type of system is generated digitally from command pulses provided by the incremental computer. Output pulse rates are monitored, and, if any should exceed the maximum rated output speed, the incoming pulse rates are decreased by means of the input buffering system. Servo power is provided by two-phase induction motors, with considerable attention given to the selection of motor size and gear ratios to insure that the servos have the necessary speed, bandwidth, and accuracy.

Aside from the real-time inputs and outputs, communication with the computer generally takes place through the whole-number section. Means of communication include the operator's control panel, the displays, a punched-tape reader, and a tape punch. The tape reader permits the rapid entry of problem data and program into the computer, and the tape punch permits the recording of selected coordinates and other data in machine-readable form.

The incremental section of the computer contains 160 integrators (in the *DDA* sense) organized into two channels of 80 integrators each. Word length is 28 bits, including sign and in some cases a parity bit. Each integrator is processed 100 times per second for an iteration rate of 100 per second.

One of the more unusual features of the computer design is the ability to assimilate up to 64 increments, positive or negative, on each interaction. This number of increments can be handled as both dependent-variable or independent-variable inputs to an integrator. The incremental computer, therefore, can handle increment rates as high as 6,400 increments per second. For many purposes, this represents an effective iteration rate of 6,400 per second.

The incremental computer also contains an additional channel of storage to assist in the generation of special functions. Such functions represent the means for handling the lens-distortion correction and the systematic corrections or mapping transformations. In both of these cases, arbitrary functions are involved. For this purpose, the functions are approximated by short straight-line segments.

Linear interpolation over any one segment is handled by standard integrators in one of the other channels. The function-generator storage channel, however, supplies slope and interval information to these integrators. A total of six arbitrary functions are required—four for the systematic corrections and two for lens distortion. The function-generator channel provides storage for a total of 320 ordinates. These ordinates may be apportioned among the six functions in any desired manner under control of the stored program.

The whole-number section of the computer is serial in operation, with a 28-bit word including sign and a parity bit. Addition time is approximately 250 microseconds, including access time for the next instruction. Multiplication time depends on the number of significant digits, but the maximum time is 6.6 milliseconds. Each instruction includes the address of the next instruction. Special instructions are included to facilitate communication with the incremental section and the operator's controls and displays.

Magnetostrictive delay lines are employed for storage in both whole-number and incremental sections. Storage capacity of the whole-number section is approximately 800 words, although it can be made larger or smaller depending on the exact functions required of the computer. The computer circuitry is fully transistorized.

Automatic Stereo Perception

As indicated earlier, the basic Helava concept is of considerable interest in systems aimed at more fully automatizing the map-making process. An important step in this regard is the incorporation of electronic-image correlation techniques for automatic stereo perception (ref 3). The analytical plotter appears to be especially well suited for integration with such techniques.

One possible system configuration is illustrated in Figure 6. As shown, the electronic correlator replaces or augments the human operator. For contouring, it produces X and Y commands for servos which drive the main carriage and which feed the computer with information to generate the differential photo-carriage motion commands.

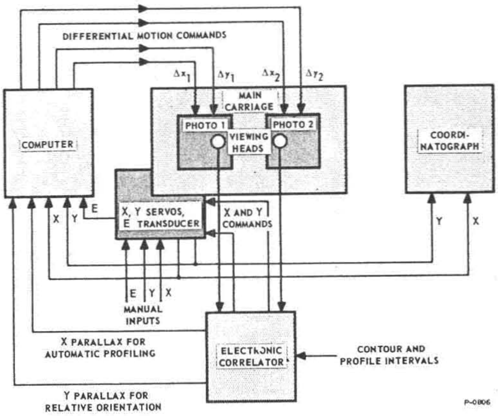

Fig. 6. Analytical plotter with electronic stereo perception.

For automatic profiling, the correlator merely furnishes to the computer a measure of x parallax. The computer then automatically adjusts the elevation command to generate differential motions which minimize x parallax and in effect keep the floating mark on the ground. Similarly the correlator furnishes a measure of y parallax to the computer for use in automatic relative orientation.

The advantages of the Helava concept in this application are due primarily to the small number and simplicity of actual physical motions required in the instrument. This same factor can be expected to make possible greater accuracy and to lead to additional advantages as the map-making process is made more automatic in other respects. Other advantages of the analytical approach result from the ease with which a wide variety of correction factors can be introduced electronically. Thus accuracy, as well as versatility, are improved. A final point to be mentioned is the ease with which the instrument can communicate in digital form with other components of an automatic map-making system.

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