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Hybrid Stereo Restitution Systems

Analogue-digital systems—a new class of restitution instruments.

ABSTRACT: *Hybrid systems, comprising analogue and digital components, constitute a new class of the stereo-restitution equipment. Such systems may provide a good balance between the capabilities and cost. They are appropriate where high accuracy or great flexibility is demanded, and for operation with automatic correlators and corresponding control units. The potentials of the analogue and digital components can be integrated into high-performing flexible systems. Tracking of photographs is supposed to be divided into coarse (fast) and differential (fine) displacements, the former being controlled by analogue (e.g., mechanical) means while the latter by a digital (e.g., less powerful) computer. This arrangement simplifies the real-time operation of the digital computer and reduces the requirements on performance of the output servos. The mechanical components can be simple but they should be stable. They need not be highly precise as the corrections for any determinable errors can be implemented by the digitally controlled differential tracking.*

INTRODUCTION

THE RECENT INTRODUCTION of electronic digital computers for processing and control in photogrammetric stereo-restitution creates new reasons for optimising the relevant equipment and methods. The problems fundamental to the conceptual stage of development and design of optimum equipment and methods concern:

- The *definition* of objectives and functions of the system and its components in given environments;
- The *assignment* of the relevant tasks to the analogue and digital components, and to the human operator;
- The *design* of an optimum system configuration and of the components.

The usual objectives for an optimum system design are: a high performance, great flexibility, high reliability, and simple maintenance. In addition there should be a balance between the work capability and the cost of equipment.

The operator's tasks are normally inspection, interpretation and generation of motions X, Y, Z—thus tracking. The scope of this paper is limited to the metric functions to be realized by the analogue and/or digital components only. Thus, they concern the flow of the metric information in a system. Problems involved in the design and construction of the automatic components replacing the human operator, such as automatic image sensing and tracking control, will not be treated here. However, some consideration will be given to the possibility of integration of such components in the hybrid systems.

The integration of digital components in the stereo-restitution systems has created a new research area for the instrument designers. Some optimized systems will presumably employ both analogue and digital components. In 1957 Helava (1957, 1958) devised the principle of the Analytical Plotter AP-1. The instrument consists of a tracking unit with an observation system similar to a stereocomparator, a computer (initially analogue, later digital) and a drawing table. The tracking unit and the computer form a feedback loop.

The operator generates x and y motions common to both photographs on the tracking unit, and Z changes which are fed directly to the computer. The common xy-motions are transmitted from the tracking unit to the

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computer which generates the differential displacements of each photocarriage ($\delta x'$, $\delta y'$ and $\delta x''$, $\delta y''$). Thus, in the AP-1 the common motions x, y are controlled directly by the operator, while the differential displacements of each photo-carriage are generated by the computer. Later the AP-C, several versions of the AP-2 (AS-11A, B, B-1, C) (Lorenz, 1967; Nowicki, 1968) and the UNAMACE (Bertram, 1964, 1968) were designed, where tracking of both photographs is controlled by digital means.

At the XI ISP Congress in Lausanne Forrest, 1968, presented a paper on the Hybrid Stereoplotter. The system consists of a conventional stereoplotter (OMI-Photomapper VI) and an analogue-digital (A-D) modification kit, developed by the Bendix Co in USA. The main components of the kit are the input sensors for the locations X, Y, Z and the Y-parallaxes, a real-time digital computer and the output servos for the corrections.

The Analytical Plotter AP-1 and the Hybrid Stereoplotter represent two opposite extreme examples in the class of the analogue-digital systems. Between these extremes intermediate solutions appear to be feasible. The hybrid stereo-restitution systems were considered also at the ITC, Delft, in the spring of 1968, thus before the development at the Bendix Co. was known. The basic concept, developed in Delft independently, differs significantly from that of the Bendix Hybrid Stereoplotter.

A survey of properties of the hybrid systems, conducted last year at the ITC, has suggested important potentials and a diversity of possible solutions. Such systems appear particularly convenient in the following (alternative) applications:

- Where the requirements on performance are high,
- Where the system has to be flexible,
- In the case of automatic image sensing and tracking control, by means of correlators and associate units.

In the next section some general properties of existing equipment are surveyed, whereas the third section is devoted to the feasible optimum hybrid systems. The conclusion will be summarized in the last section.

Known Systems

The existing instruments may be classified according to the functions of the analogue and digital components in the metric flow, into:

Analogue systems (optical, mechanical, partly optical-partly mechanical),

Digital systems—where tracking of photographs is controlled digitally,

Hybrid systems—where tracking of photographs is realized partly by analogue and partly by digital means.

ANALOGUE SYSTEMS

Conventional projection type instruments and those employing other analogue computers belong to this class. The merits of such instruments are:

Ease of controlling rapidly changing locational parameters (tracking);

Conventional procedures can be used;

Cost of equipment is normally moderate.

Some disadvantages are:

Flexibility is rather restricted;

Number of parameters in the process is practically limited (e.g., for various corrections);

Accuracy has physical limitations due to comparatively long chains for the metric flow (accumulation of errors, lower stability of analogue components);

Performance degrades with time and use;

Maintenance may be time-consuming and costly.

DIGITAL SYSTEMS

—Instrument types belonging to this class are the various versions of the Analytical Plotter AP-2 (or AS-11) and AP-C, and the UNAMACE (Universal Automatic Map Compilation Equipment) of Bunker Ramo Co. The merits of the digital systems are:

Flexibility regarding the mathematical models, types of inputs and outputs, and the parameters in the process. The flexibility is limited mainly by the power of the computer.

Number of the mechanical error sources is rather low—hence good stability and high precision can be achieved,

A least-squares fit can be realized automatically in the presence of redundant data; hence, the accuracy can be increased and estimated,

Relevant instrumentation can be packaged in compact modules suitable for transport.

Maintenance of the analogue components is comparatively easy and inexpensive.

The disadvantages are the following:

If insufficiently powerful computers are employed the computation speed for the control of the rapidly changing parameters can be critical.

Dynamic performance (time response) of the output servos in fast operation may be unsatisfactory.

Cost of a digital computer having sufficient power and of high-performing output servos is rather high.

By a comparison of the listed properties of the analogue and digital systems it follows that the potentials of both approaches are complementary. Consequently their components can be integrated into hybrid systems such that the demerits will be eliminated to a great extent.

HYBRID SYSTEMS

At present there is only one analogue-digital system known, the Bendix Hybrid Stereoplotter (Forrest, 1968). The objective for the design of the A-D (analogue-digital) modification kit was to facilitate the *corrections* to model coordinates (XYZ) and to a base component *by* (of the right-hand projector), for various metric distortions. These distortions may originate in the photographs, projection system, relative and absolute orientation, and in the earth curvature and atmospheric refraction. In the present program the integral effect of all these distortions is approximated by second-order polynomials for the four parameters, XYZ and *by*. The coefficients of these polynomials are computed from the coordinate discrepancies in given control points and from the Y-parallaxes in several orientation points. For this purpose the method of least squares is used. The corresponding corrections are accomplished by means of a servo-positioning network.

The merits of the Hybrid Stereoplotter are the following:

Higher flexibility than analogue systems.

One computer may serve several plotters simultaneously.

For the computation of coefficients of the correction model, redundant data can be used.

The overall accuracy of the system can be improved with respect to the pure analogue instruments.

The disadvantages are:

For the determination of the coefficient of the correction model, sufficient and accurate control data must be available. Therefore this hybrid approach is less suitable for restitutions with little control data.

Combination of a conventional projection-type plotter having rather limited performance and stability, with a digital computer, appears to be unbalanced. The digital computer cannot compensate for the high level of the stochastical errors nor the instability of the mechanical components.

The expected cost of such systems is comparatively high due to the full cost of the stereoplotter, the additional interfaces between the stereoplotter and the computer, and the share of the computer itself.

Considerable maintenance may be required for the stereoplotter, the interfaces and the computer.

The Bendix hybrid system is thus an approximate realization of the metric transformations by means of the projection system of a stereoplotter, where the relevant corrections are generated and controlled according to a simplified mathematical correction model, by a digital computer. The computer acts via the interfaces only as a versatile and flexible correction unit. From the summary of properties of the Bendix Hybrid system it follows that the analogue and digital components have not been combined in full consideration of their potentials in order to provide an optimum system configuration.

Optimum Hybrid Systems

GENERAL CONSIDERATIONS

To optimize a hybrid system means to synthesize a configuration, consisting of analogue and digital components and their interfaces, so that their potentials are exploited and the demerits are greatly eliminated. From the summary of the properties of analogue and digital systems presented earlier, it follows that the analogue components are convenient for manipulation of the rapid and continuously changing control parameters, whereas the digital components are more suitable for accurate control of the variables that change slowly in a restitution process. Thus it seems expedient that the analogue components provide a high stability and consequently a good dynamic performance, whereas the digital components should facilitate a high accuracy and sufficient flexibility.

As *analogue* components, stable simple mechanical computers can be employed, realizing approximately the metric relations between the photographs (or other image records) and the model space. These relations must be accurately defined and should remain unchanged over long periods of time. The carriages for the *coarse* (*fast*) *tracking* of photographs can be coupled mechanically to the *analogue* computers in order to omit the servos.

The *differential* (*fine*) *tracking* can be generated and controlled by means of a *digital* computer. It may be performed at a comparatively slow speed, depending on the design of the analogue computers. This reduces the demands on the sampling rate of the digitizers, the computation speed and on the time response of the output servos. However, a slow operation does not necessarily result in a simplification of the mathematical models and the corresponding computer program, but it avoids the difficulties involved in high sampling rate, high-speed computation and fast servo control. The limits between the coarse and differential tracking are flexible, thus facilitating a wide range of solutions. Depending on the complexity of the analogue computers, the power of the digital computer and the dynamic performance of the interfaces, different solutions can be implemented. A simplified mechanical computer results in less accurate coarse tracking—therefore more and faster differential tracking will be required. This introduces higher demands on the digital computer and on the output servos. Conversely, a slow-operating digital computer and/or low performing servos require better approximations of the mechanical computers. In optimum solutions the analogue and digital components should be appropriately balanced.

In the following a conceptual approach to the design of an optimized hybrid system will be made.

ALGEBRAIC FORMULATION OF THE PROBLEM

The resolving of motions on coarse and differential tracking can be formulated algebraically by

$$\begin{aligned} x' &= x_a' + \delta x' \qquad & y' &= y_a' + \delta y' \\ x'' &= x_a'' + \delta x'' \qquad & y'' &= y_a'' + \delta y'' \end{aligned} \tag{1}$$

where x, y are the correct (desired) locations of the tracking devices for the photographs, x_a, y_a, are the approximate locations provided by the analogue (mechanical) computers, and δx, δy represent the digitally controlled differential displacements. For the conventional central perspective (frame) photography the correct locations of the tracking devices are defined by:

$$\begin{aligned} \begin{bmatrix} x' \\ y' \\ c' \end{bmatrix} &= \lambda' A' \begin{bmatrix} X - X_0' \\ Y - Y_0' \\ Z - Z_0' \end{bmatrix} + \begin{bmatrix} \text{corrections} \\ (1) \end{bmatrix} \\ \begin{bmatrix} x'' \\ y'' \\ c'' \end{bmatrix} &= \lambda'' A'' \begin{bmatrix} X - X_0'' \\ Y - Y_0'' \\ Z - Z_0'' \end{bmatrix} + \begin{bmatrix} \text{corrections} \\ (2) \end{bmatrix} \end{aligned} \tag{2}$$

In the above relations x, y are the photo-coordinates with the principal point as the origin, c is the principal distance, λ is the scale factor (photo-to-model), A is the rotation matrix,

$$A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix},$$

XYZ are coordinates of an arbitrary model point, and $X_0Y_0Z_0$ are the coordinates of the perspective center ($X_0'' = X_0' + bx$, $Y_0'' = Y_0' + by$, $Z_0'' = Z_0' + bz$).

Relations 2 are fulfilled to a large extent in the conventional projection type instruments. However, there are practical limitations for the implementation of the corrections. Usually only facilities for correcting lens distortion are provided. In principle, arbitrary corrections could be applied numerically to the model coordinates at a later stage. This would result, however, in an off-line hybrid system.

An on-line digital computer facilitates corrections during operation for arbitrary determinable errors including those originating in the analogue component of the system. The analogue components can therefore be simple constructions. The function of the analogue computers (coarse tracking) can be formulated in algebraic terms, e.g., by:

$$\begin{aligned} x_a &= \frac{(X - X_0')}{\bar{Z}} \bar{c} \qquad & y_a' &= \frac{(Y - Y_0')}{\bar{Z}} \bar{c} \\ x_a'' &= \frac{(X - X_0'')}{\bar{Z}} \bar{c} \qquad & y_a'' &= \frac{(Y - Y_0'')}{\bar{Z}} \bar{c} \end{aligned} \tag{3}$$

$\bar{Z}$ and $\bar{c}$ are the projection and principal distances set in the analogue computers. By subtracting the Equation 3 from 2, the algebraic model for the differential tracking is obtained:

$$\begin{aligned} \delta x' = {} & \lambda'[a_{11}'(X - X_0') + a_{12}'(Y - Y_0') \\ & + a_{13}'(Z - Z_0')] - (\bar{c}/\bar{Z})(X - X_0') \\ & + \text{corrections in } x' \\ \delta y' = {} & \lambda'[a_{21}'(X - X_0') + a_{22}'(Y - Y_0') \\ & + a_{23}'(Z - Z_0')] - (\bar{c}/\bar{Z})(Y - Y_0') \\ & + \text{corrections in } y' \\ \delta x'' = {} & \lambda''[a_{11}''(X - X_0'') + a_{12}''(Y - Y_0'') \\ & + a_{13}''(Z - Z_0'')] - (\bar{c}/\bar{Z})(X - X_0'') \\ & + \text{corrections in } x'' \\ \delta y'' = {} & \lambda''[a_{21}''(X - X_0'') + a_{22}''(Y - Y_0'') \\ & + a_{23}''(Z - Z_0'')] - (\bar{c}/\bar{Z})(Y - Y_0'') \\ & + \text{corrections in } y'' \end{aligned}$$

A convenient solution is to make $\bar{c} = c' = c''$ and $\bar{Z} = Z$. The Equations 3, to be realized (e.g., mechanically) can be chosen differently. Each choice results in another solution of the system. If non-conventional (e.g. dynamic) photography is used, both Equations 2 and 3 have to be replaced by appropriate algebraic models.

SYSTEM CONFIGURATION

A *system* operated *manually* (Figure 1), consists of the tracking unit, analogue com-

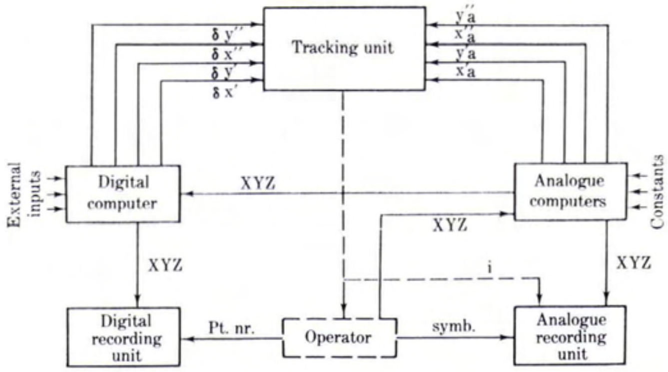

FIG. 1. Configuration of a manually operated system.

puters, a digital computer, recording units and the interfaces. The tracking unit and the analogue computers can be connected by simple mechanical links.

The changes of X, Y, and Z in the model space, generated by a human operator, are fed to the analogue computers and from them they are transferred to the plotting device (in Fugure 1 labelled by analogue recording unit). The analogue computers control the coarse tracking (x_a', y_a' and x_a'', y_a'') of both photographs.

The *digital computer* receives instantaneously the values of the model coordinates XYZ from the analogue computers. Constants concerning the geometry of photographs and the settings of the analogue computers can be introduced (external inputs). The outputs of the digital computer are signals for the differential tracking $\delta x', \delta y'$ and $\delta x'', \delta y''$ (the digitizers and the output servos are not represented in the figure). The digital computer may also serve for automatic control of the coordinate recording. The stored model coordinates can be further processed if desired.

In the profiling mode of operation the digital computer can control traversing and stepping. Further it may control the optical units for the corrections of image distortions due to terrain slope and geometry of photgraphs. For convergent photography, the digital computer can generate signals for the control of the optical elements to facilitate a convenient stereoscopic observation.

Regarding the type of the digital computer as a part of the hybrid system there are two main possibilities:

- An existing or a commercially available computer is used.
- A specially designed computer is employed.

In the first instance the power of the computer general considerably exceeds the need for control of the slow-changing parameters. Due to the lower demands on the computer capacity in differential tracking, than in full control of the locational parameters, essentially more capacity for other computational and control tasks is left. An economic solution would be, e.g., the use of the computer for the control of several hybrid systems and/or automatic coordinatographs or ortho photo printers simultaneously on a time-sharing basis.

Where a digital computer is being constructed specially for the control of a hybrid system its power can be matched with the real needs for performing the intended functions. Employment of efficient electronic circuits may result in a simple configuration and a compact computer.

The *tracking unit* of the suggested system consists of the photo-carriers, carriages with corresponding guiding ways and driving agents, and the observation system. The carriages and guiding ways can be arranged differently. Tracking may be performed by means of the photo-carriages, by the carriages with optical units or combined. In total there are eight motions to be realized, four for each photograph (x_a, y_a, δx, δy); therefore many combinations are possible. A convenient solution is to perform the coarse tracking (x_a, y_a) by the photo-carriages and the differential tracking (δx, δy) by the carriages with optical units. This choice is related to the functions of the mechanical and digital computers. Another suitable approach is to apply coarse tracking partly to the photo-carriages (e.g., in x) and partly to the carriages with optics (in y). The differential tracking would also be divided between the photo-carriages (e.g., in y) and the carriages with optics (in x).

If the photographs are not accurately centered in the photo-carriers the digital

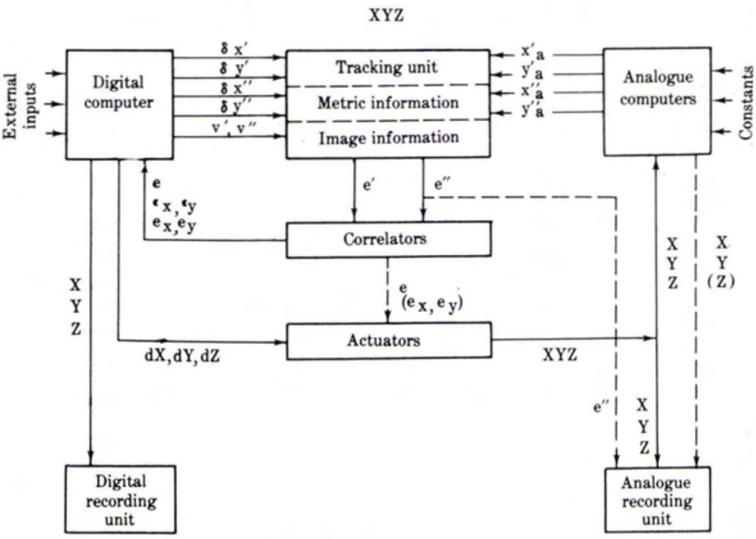

FIG. 2. Configuration of an automated system.

computer can provide the corresponding corrections (as e.g., in the Analytical Plotters). The guiding rails need not be precise and no facilities for mechanical adjustment are necessary. However, the tracking unit should be stable. Corrections for all determinable errors can be applied by differential tracking. For observation a simple comparator-type optical system is convenient.

Simple mechanical constructions, providing a high stability, are convenient as *analogue computers*. A simplified projection system, preferably solved in horizontal planes, seems to be feasible. A solution similar to that of the Zeiss-Orel Stereoautograph, with some simplification for better stability, would be appropriate. Different choices can be made regarding the analogue orientation facilities, reflecting the mathematical models for the coarse tracking (e.g., Equations 3). Some values for the orientation parameters can be introduced. The most simple solution would use a constant principal distance $\bar{\phi}$, zero tilts $\bar{\zeta}=\bar{\omega}=O$, and zero base components $\bar{b}y=\bar{b}z=O$ (bars above symbols refer to the instrumental settings). Another solution may provide for variable principal distances and zero values for other orientation parameters (except the base b). A further solution, not represented by the Equations 3, is: variable principal distance $\bar{c}$ and variable $\bar{\phi}$ (for convergent photography) or variable $\bar{\omega}$ (for oblique photography). Apart from these other solutions can be implemented.

The mechanical computers need not be manufactured precisely as corrections can be applied for their imperfections by the differential tracking. Hence, the facilities for mechanical adjustment need not be provided, but the determinable errors should be calibrated. The mechanical analogue computers and the tracking unit can be packaged in a common module.

An *automatically operated system* is represented in Figure 2. The configuration is similar to that of the manually operated systems (Figure 1) only the human operator being replaced by the automatic correlators and the servos being used as the actuators. The tracking unit is supposed to be provided with optical-electronic (or other) scanners and photo-multipliers, generating the video signals e', e'' for the correlators. The digital computer can control the adaption of scans (v', v'') such that the conjugate imagery will be scanned. This control is based on the correlation signal e, the slope signals ϵ_x, ϵ_y generated by the correlators, and the geometry of photographs (external inputs).

The correlation e and the parallax signals e_x, e_y, produced by the correlators, are fed either to the digital computer for the digital control of the output servos (actuators), or directly in analogue form to the servos. In the latter case the interfaces between the digital computer and actuators can be omitted.

The actuators may generate alterations in height (in parallax Px) and in the relevant orientation parameters (Py-parallax, not shown in Figure 2).

If optical-electronic scanners are employed, the differential tracking can be carried out electronically. The signals on δx, δy, generated by the digital computer, may be converted into voltages for the deflection coils of the scanning cathode-ray tubes. Consequently the scans would be instantaneously displaced from the zero-positions over δx and δy. The actuators, analogue computers and the tracking unit can be packaged in one module, and the correlators and the digital computer in another.

Conclusion

A diversity of analogue-digital restitution systems can be developed. Each system may provide a good balance between the potentials and the cost of the equipment in view of the intended applications. However, such systems appear to be particularly appropriate if high accuracy and/or great flexibility are demanded. In addition optimized hybrid systems are suitable for operation with automatic correlators and control units due to the potentials of the digital computer and the simple arrangement of the tracking unit. The performance of the hybrid systems can be high if the process for the metric information is properly designed. This may be achieved by dividing the tracking of photographs into coarse and differential fine-tracking.

The chain of the analogue (e.g., mechanical) components, through which the signals for coarse tracking flow, should be short and stable. The differential tracking is supposed to be digitally controlled; hence, a high accuracy and sufficient flexibility could be provided. Such an arrangement simplifies the real time operation of the digital computer and reduces the performance requirements on the output servos due to the lower demands on speed. However, the mechanical components of the system should be highly stable.

The construction of the mechanical computers for the metric transformation of the rapidly changing parameters can be simple. The cost of the hybrid systems is expected to be lower than the cost of the digital systems as the mechanical components need not be manufactured with high precision, and the demands on performance of the digital computer and the interfaces are comparatively low. In comparing the hybrid and digital systems, one might expect the former to be less accurate due to the higher probability of unconsidered errors in the analogue components. However, the slowly operating servos of the hybrid systems will apparently perform better than those used in the digital systems. Thus the two systems will presumably produce comparable accuracy.

Optimum stereo-restitution systems can be achieved by a good balance between the analogue and digital components and between their potentials and the cost of purchase and maintenance.

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