NETWORK DESIGN OPTIMIZATION IN NON-TOPOGRAPHIC PHOTOGRAMMETRY

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ABSTRACT

Given accuracy objectives for a photogrammetric project, the planned network must be designed in an optimal manner. In this paper the design problem is addressed in terms of four classes of design: the zero-, first-, second- and third-order problems. These design classifications are discussed in the context of analytical non-topographic photogrammetry. Specific network characteristics are outlined and design through simulation is discussed. The STARS simulator package developed by Geodetic Services, Inc., is also briefly described.

INTRODUCTION

Of central importance in the design of a multi-station, non-topographic photogrammetric network is the overall quality of the network. The quality, in turn, can be expressed through a number of target functions. To name four: precision, reliability, economy and testibility (e.g. SCHMITT, 1981). In judging whether a design is optimal in some sense, the planner must ensure that user-specified requirements regarding some or all of these target functions are realized.

Of the target functions mentioned, precision is determined at the design stage through the choice of an observation scheme for the network, i.e. through the networks geometric configuration and the accuracy with which observables can be measured. The interrelated reliability problem is concerned with the quality of conformance of an observed network to its design, i.e. to what degree the network is self-checking. At the design stage, optimization in the area of economy is not usually explicitly addressed, and the testibility criteria laid down can usually be incorporated implicitly in the examination of network precision.

In this paper, which is essentially a shortened version of FRASER (1983), the problem of network design as it related to the optimization of precision is primarily addressed. In this process one is concerned with ensuring that the quality of the network design is sufficient to enable user-specified accuracy requirements to be met.

Following the widely accepted classification scheme of GRAFAREND (1974), the general network design optimization process can be considered to be comprised of four interconnected stages:

Zero-Order Design (ZOD)	-	the datum problem
First-Order Design (FOD)	-	the configuration problem
Second-Order Design (SOD)	-	the weight problem
Third-Order Design (TOD)	-	the densification problem

In spite of the fact that the four orders of design are linked through a number of interrelated aspects, the classification scheme above is widely accepted, and the sequence is essentially chronological. As will be shown, however, the design optimization process for non-topographic photogrammetric networks need only consider in detail the ZOD and FOD stages in most practical situations.

In order to fulfil specified precision requirements a solution for the problems associated with the four design classes is sought. One of two approaches is usually adopted in this regard, either computer simulation or analytical methods. Considerable research attention is currently being directed at strategies which involve a direct mathematical solution for one or more of the design problems encountered in geodetic networks. However, analytical methods exhibit both some theoretical and practical difficulties, and most present work seems to be in the area of SOD, the design problem that is often greatly simplified for photogrammetric networks.

A more practicable and well-suited method of design involves network simulation. Through simulation a preanalysis of the propagation of uncertainties in the observations to uncertainties in the final parameters can be carried out. In this way precision can be both accurately predicted and compared to the accuracy specifications for the design. The optimization process then involves, initially, the approximation of a "good" solution to the specific design problem. This solution is subsequently refined and updated in an iterative manner, using a combination of trial and error and established design guidelines, until the design objective is attained in an optimal manner. One disadvantage of this approach is the potential time delay between the separate "iterations" carried out. The advent of powerful desk-top computers with interactive graphics terminals has, however, both largely removed this time hindrance, and opened up the possibility for effective real-time computer-aided design (CAD). Such a simulation package for network design in high-precision close-range industrial photogrammetry has been introduced by Brown (1982).

In this paper, salient aspects of the four design classifications as they relate to non-topographic photogrammetric networks are outlined and the process of interactive network planning through CAD is discussed. Features of the STARS simulator developed by Geodetic Services, Inc. are also briefly outlined.

ZOD - THE DATUM PROBLEM

By referring to the standard parametric model for the self-calibrating bundle adjustment, the different orders of design can be identified in terms of fixed and free quantities within the adjustment process. The linear functional and stochastic model can be written as

$$\underline{v} = \underline{A}\,\underline{x} - \underline{\ell} \quad \text{and} \quad \underline{C}_{\ell} = \sigma_o^2\, \underline{P}^{-1} \tag{1}$$

where $\underline{\ell}$, $\underline{v}$ and $\underline{x}$ are the vectors of observations, residuals and unknown parameters, respectively; $\underline{A}$ is the design or configuration matrix; $\underline{C}_{\ell}$ the covariance matrix of observations, $\underline{P}$ the weight matrix; and σ_o^2 the variance factor. In situations where $\underline{A}$ is of full rank, i.e. redundant or explicit minimal constraints are imposed, the parameter estimates $\hat{\underline{x}}$ and the corresponding covariance matrix $\underline{C}_x$ are obtained as

$$\hat{\underline{x}} = (\underline{A}^T\underline{P}\underline{A})^{-1}\, \underline{A}^T\underline{P}\underline{\ell} = \underline{Q}_x\underline{A}^T\underline{P}\underline{\ell} \quad \text{and} \quad \underline{C}_x = \sigma_o^2\, \underline{Q}_x \tag{2}$$

where $\underline{Q}_x$ is the cofactor matrix of the parameters. If $\underline{A}$ has a datum defect of rank, a Cayley inverse of the singular normal equations is not possible and some form of free-network approach employing implicit minimal constraints (e.g. through generalized inverses) is adopted.

The datum problem or ZOD involves the choice of an optimal reference system for the object space coordinates, given the photogrammetric network design and the precision of the observations. That is, for fixed $\underline{A}$ and $\underline{P}$ one usually seeks, through the selection of an appropriate datum, an optimum form of the cofactor matrix $\underline{Q}_x$. Zero-order design is appropriate in photogrammetric networks which are not "hung" on existing object space control frameworks, i.e. where the datum information introduced into the network adjustment is not sufficient to introduce a change in shape of the relatively oriented bundles of rays. Through ZOD an XYZ reference coordinate system is assigned to the network by the imposition of minimal datum constraints. The zero-variance computational base of this system requires the implicit or explicit definition of an origin, orientation and scale for the XYZ cartesian coordinate system. The datum problem hinges on the fact that as the zero-variance computational base is altered, so the cofactor matrix $\underline{Q}_x$ of the network parameters changes. It must be recalled that the primary system observables, namely photo coordinates, do not contain any information about the datum.

Whereas parameters of shape are determined solely as a function of system observations, and are therefore invariant with changes in the imposed minimal constraints, object space coordinates relate to the datum, which means that both $\underline{\hat{x}}$ and $\underline{Q}_x$ change with changes in the minimal control configuration. If the minimal control is to be arbitrarily assigned, ZOD can involve the process of establishing a zero-variance computational base for the XYZ coordinate system which is optimum in some sense. This procedure typical comprises finding a "best" form for the cofactor matrix $\underline{Q}_{x2}$ of either all the XYZ object point coordinates or a subset thereof. Emphasis is placed on optimizing $\underline{Q}_{x2}$, rather than $\underline{Q}_x$, since the parameters of primary interest are typically object point coordinates and functions of these coordinates, e.g. deformations, distances, etc.

The question of which is a "best" form for $\underline{Q}_{x2}$ is much dependent on the user-specified accuracy objectives for the established network. For example, one case may call for a covariance matrix of the object points which displays a maximum homogeneity of precision, whereas another may stress the optimization of variance in a single coordinate axis. The planner should tailor his ZOD to meet the precision criteria laid down. Four approaches are available in this regard:

- Generalized inverses,
- Inner constraints,
- Arbitrary minimal control via "preferred" points, and
- S-Transformations.

The pseudo or Moore-Penrose inverse is the most commonly applied member of the generalized inverse family for network design. This solution for $\underline{x}$ explicitly yields minimum mean variance for the parameters, i.e.

$$\bar{\sigma}_x^2 = \frac{\sigma_o^2}{m}\, tr(A^T PA)^+ = \frac{\sigma_o^2}{m}\, tr\, \underline{Q}_x \rightarrow \text{minimum} \quad (3)$$

where m is the number of parameters. As has been pointed out, for example, in FRASER (1982) minimum $\bar{\sigma}_x^2$ may not represent a "best" criterion for the ZOD. This is because all parameters are included in the datum definition, and not just object point XYZ coordinates. To achieve a minimum trace for $\underline{Q}_{x2}$, exterior orientation and additional parameters need to be eliminated so the pseudo inverse is computed for only a reduced set of normal equations. Given the structure of most fold-in algorithms employed for the solution of bundle adjustment normal equations, whereby the object point vector $\underline{x}_2$ is eliminated, such an approach can pose algorithmic difficulties. An equivalent, more computationally attractive approach to this so-called "main" solution is the method of inner constraints (e.g. BLAHA, 1971), which has recently been applied in close-range photogrammetry (e.g. BROWN, 1982; FRASER, 1982 and PAPO & PERELMUTER, 1982). In addition to yielding optimum mean object point precision:

$$\bar{\sigma}_c^2 = \frac{\sigma_o^2}{3n} \operatorname{tr} Q_{x2} \rightarrow \text{minimum} \tag{4}$$

where n is the number of points, a minimum Euclidean norm of the object point coordinate corrections is obtained. The inner constraints need not apply to all object points, and the imposition of this implicit minimal control may simply refer to a chosen subset of the target array (three points is naturally the minimum number).

In view of the fact that the "main" solution yields minimum mean variance, one may validly ask whether this free-network approach provides a solution to the datum problem. For numerous applications it may, and in the case of relative deformation networks (all points assumed unstable) free-network adjustment is advantageous (e.g. FRASER, 1983a; FRASER & GRÜNDIG, 1984). But, much depends on the criteria set for $\underline{Q}_{x2}$ at the ZOD stage. For example, the common, computationally simpler approach of "fixing" object point coordinates of "preferred" points to remove the seven (six if distances are observed) network defects of translation (3), rotation (3) and scale (1) will yield a mean variance $\bar{\sigma}_c^2$ for the object points which is larger in magnitude than that obtained from the inner-constraints adjustment. Differences in the precision of parameters (e.g. distances) derived from $\hat{\underline{x}}_2$ may, however, be insignificant from a practical point of view.

Through the use of an S-transformation, introduced by BAARDA (1973), it is always possible to transform both $\hat{\underline{x}}_2$ and $\underline{Q}_{x2}$ relating to one zero-variance computational base, into their corresponding values for any other minimal constraint. For example, after the cofactor matrix of object point XYZ coordinates is computed for a datum of seven explicitly fixed coordinate values, the corresponding "main" solution for $\underline{Q}_{x2}$ is obtained simply by applying an S-transformation. Although the implementation of covariance transformations is relatively straightforward (e.g. STRANG VAN HEES, 1982), the S-transformation does necessitate the computation of a full $\underline{Q}_{x2}$ matrix. Thus, for close-range photogrammetric networks with dense target arrays where coordinate variances and not covariances are sought, it is often computationally more practical to readjust the network with a different datum rather than apply an S-transformation. The S-transformation is very applicable, however, when it is required to transform an ideal, or criterion matrix into one which refers to a specific minimal constraint.

The impact on object point precision of changes in the ZOD of a minimally controlled close-range photogrammetric network has been illustrated quantitatively in FRASER (1982, 1983), and the reader is referred to these papers for further details. Here, only a few important observations from this previously conducted experimental work are noted:

- Changes in ZOD, i.e. in the applied minimal constraint configuration, not only influence the magnitude of object point coordinate standard errors, but also the degree of homogeneity of the network precision. In this regard, inner constraints provide a "best" solution, in addition to yielding maximum mean precision (minimum $\bar{\sigma}_c$).

- In both "normal" and convergent configurations, free-network adjustment can yield higher mean precision than that obtained in networks with either redundant object point coordinate control, or point-to-point distance observations. This is an important property given that the establishment of other than an arbitrary minimal constraint requires extra surveying work.

- An "optimum" minimal control configuration of two "preferred" points fixed in XYZ and one fixed in Z (or X or Y) is likely to be approached when the centroid of the triangle formed by the three object control points is reasonably close to the target array centre, and the triangle's area is a maximum.

- For favourable minimal control configurations the variation in the precision of certain functions of $\underline{Q}_{x2}$, which accompany changes in the datum, can be expected to be somewhat less than the variation in $\bar{\sigma}_c$. This is notably the case with point-to-point distance precision.

In concluding this section on ZOD the point must be made that the datum problem is not independent of the configuration problem. The extent to which a change in datum will influence object point precision is very much dependent on imaging geometry. In general, a change in the zero-variance computational base seems to influence the precision of "normal" networks to a greater degree than the inherently more homogeneous convergent configuration, especially in the case of an unfavourable minimal constraint.

FOD - THE CONFIGURATION PROBLEM

The configuration problem or FOD is concerned with the search for an optimal geometry, given both the precision of the observations, and objectives for the structure of either the covariance matrix $\underline{C}_x$ or the corresponding cofactor matrix $\underline{Q}_x$. Thus, this procedure entails finding an optimal design matrix $\underline{A}$, given a weight matrix P, subject to specified criteria for the structure of $\underline{Q}_x$. In non-topographic photogrammetry, FOD embraces such aspects as imaging geometry, the number and location of object target points, camera selection and the influence of self-calibration in the network adjustment.

Of primary concern is typically the choice of an appropriate imaging configuration for a given array of object target points. The usual aim here is to find a configuration matrix $\underline{A}$, which for a given $\underline{P}$ yields a desired structure for $\underline{Q}_{x2}$. For example, the design criterion may be that $\underline{Q}_{x2}$ is to be both homogeneous and isotropic, i.e. all point error ellipsoids are spheres of equal radius.

Although its principal component is imaging geometry, FOD also embraces a number of the well-recognized methods for enhancing object point precision. These include the adoption of larger image scales and long-focal length photography, the use of target clusters around an object point, and multiple exposures at each camera station. The latter aspect can also be interpreted as a component of the second-order or weight problem, much like the multiple measurement of image coordinates. Also, in terms of optimizing precision (but not necessarily reliability) the use of target clusters can be considered as part of the TOD process. A further, important aspect of the configuration problem is the influence of additional self-calibration parameters (APs) - be they block-invariant or sub-block invariant, coefficients of general polynomial functions or physically interpretable camera calibration parameters - on the precision of object point determination. The following papers address various accuracy enhancement approaches which can be classified as part of the FOD procedure: KENEFICK (1971), HOTTIER (1976) GRÜN (1978, 1980), FRASER (1980), BROWN (1980), GRANSHAW (1980), TORLEGÅRD (1981) and VERESS & HATZOPOULOS (1981). In briefly discussing the configuration problem it is useful to consider the above mentioned aspects under separate headings.

Imaging Geometry

The adopted imaging geometry for a network is a central factor in determining the object point positioning accuracy. A number of authors have highlighted the well recognized accuracy discrepancy between "normal" and multi-station convergent imaging configurations. However, in the context of FOD it is not so much the impact of different geometries on the magnitude of $\bar{\sigma}_c$ that is of prime interest, but more the relationship between the standard errors σ_X, σ_Y and σ_Z of the object point coordinates. A simple scaling of $\underline{Q}_{x2}$ can be achieved through either alternative FOD options or via SOD, but the fundamental distribution of relative object point and point coordinate accuracies is established once the imaging geometry is in place.

From the results presented in FRASER (1983), which pertain to the influence of imaging geometry on the homogeneity of object point coordinate precision, a few features will be briefly noted. First, for a near-homogeneous distribution of object space precision to be obtained, a convergent imaging geometry is mandatory. However, depending on the number of photographs, a considerable range of convergence angles can be tolerated. Also, a range of convergence angles will produce a near isotropic form of $\underline{Q}_{x2}$, but such a structure cannot be attained from a "normal" configuration. For the majority of three-dimensional measuring tasks, a near-homogeneous, isotropic $\underline{Q}_{x2}$ would constitute an optimal solution to the imaging geometry problem of FOD. As a further point, it is not surprising that the homogeneity of the precision of functions of the XYZ coordinates, e.g. distances or coordinate differences, is generally optimal when a reasonably homogeneous distribution of object point positioning accuracy is designed for.

Base/Distance Ratio

It is well recognized that an increase in the B/D ratio for "near-normal" imaging configurations is accompanied by both an improved level of mean object point precision (e.g. HOTTIER, 1976) and enhanced reliability (GRÜN, 1978; 1980). As the base increases, so $\bar{\sigma}_c$ is decreased in value non-linearly. The improvement in precision, primarily in the "depth" or Z-direction, is achieved because of the more favourable ray intersection geometry. Due to the restrictive geometry of a "normal" network, alterations in the B/D ratio provide one of the few means for substantially enhancing the distribution of positioning accuracy.

Number of Camera Stations

The practice of using multi-station photogrammetric networks, as opposed to single stereopair configurations, is well established in precision non-topographic photogrammetry. Depending on the imaging geometry adopted, the use of additional camera stations can be expected to not only improve precision, but also to significantly enhance the network's reliability. An examination of accuracy improvements which accompany the use of an increasing number of exposure stations cannot, however, be divorced from a consideration of the corresponding changes in imaging geometry. Additional imaging rays increase the redundancy in a spatial intersection, and also alter the intersection geometry.

Notwithstanding the difficulties of considering in isolation the influence on FOD of the number of camera stations, one general observation that can be made is that for "strong" networks, the accuracy improvement obtained over a two-photo geometry is approximately proportional to $m^{\frac{1}{2}}$, where m is the number of photographs. This implies that if the number of camera stations is increased from two to three a significant improvement in object point precision can be expected, whereas a change from three to four photos is only likely to decrease $\bar{\sigma}_c$ by about 20%. The inverse proportionality between $\bar{\sigma}_c$ and $m^{\frac{1}{2}}$ only holds approximately, however, and is not applicable to all network designs. With this fact in mind, it seems reasonable to assert that in the FOD process more attention should be paid to the imaging geometry, rather than concentrating too much on obtaining a coverage of a certain arbitrary number of photographs, with the restriction of course that a minimum of three intersecting rays (not in the same epipolar plane) at each object point is highly desirable.

Multiple Exposures

The use of multiple exposures at a camera station provides a practical means of enhancing network accuracy. In situations where successive exposures cannot be assumed to be taken at precisely the same orientation and position, an additional set of exterior orientation parameters is introduced into the network for each successive photograph. Thus, at the design stage $\underline{A}$ is modified and so the process of selecting how many exposures should be taken becomes one of FOD. However, if the same number of exposures, k, is taken at each camera station, the influence on network precision is essentially equivalent to adjusting the single-exposure configuration with a weight matrix $\underline{P}_k = k\,\underline{P}$. The cofactor matrix is then obtained as

$$\underline{Q}_{xk} = (\underline{A}^T\underline{P}_k\underline{A})^{-1} = k^{-1}(\underline{A}^T\underline{P}\underline{A})^{-1} = k^{-1}\underline{Q}_x \qquad (5)$$

where $\underline{Q}_x$ corresponds to one photograph per station, and $\underline{Q}_{xk}$ to k exposures per camera station. Leading directly from Equation 5 is the relationship

$$\bar{\sigma}_{ck} = k^{-\frac{1}{2}}\,\bar{\sigma}_c \qquad (6)$$

Since the use of multiple exposures leads to simply a scaling of the weight matrix $\underline{P}$, the process can be considered as a component of SOD, and a few further remarks will be made on this design aspect in the section dealing with the weight problem.

Number of Points

In bundle adjustments of well designed photogrammetric networks, which do not incorporate self-calibration, the number of object points has surprisingly little impact on the mean standard error $\bar{\sigma}_c$ (e.g. FRASER, 1983). Due to this practical independence of object point precision and the number of target points, networks which are planned to include hundreds of points can be examined and optimized at the FOD stage by considering only say 20 - 40 well distributed targets. This leads to considerable savings in the computation of a representative $\underline{Q}_{x2}$.

Whereas the accuracy attained in a standard bundle adjustment is not significantly influenced by the number of target points, the precision yielded in a self-calibration adjustment is considerably affected by both the density and distribution of the object points. In the majority of systematic error compensation models employed for self-calibration, the coefficients of the APs are expressed as functions of the image coordinates. The self-calibration process can be thought of as a surface fitting problem, albeit one which is not independent of photogrammetric resection and intersection. Consider for example lens distortion. The distortion pattern of a lens is quantified by the resulting image point displacements at the film plane. Thus, if a function is required to describe this pattern throughout the entire frame format, so image points will need to be sufficiently well distributed on the film, and this in turn impacts on the distribution and number of object points imaged.

Target Clusters

The use of clusters of targets rather than a single object point has been proposed as a practical means of enhancing network accuracy (e.g. HOTTIER, 1976; TORLEGÅRD, 1981). In the presence of local systematic error influences in the imaging and measuring systems, such an approach has its merits. For example, the ability to locate observation outliers (i.e. the internal reliability) can be expected to be enhanced by using target clusters. However, for favourable imaging geometries, the influence on object point precision of an increase in the number of targets, be they clustered or otherwise, is typically insignificant. At the FOD stage, therefore, the use of target clusters generally need not be considered in a network simulation, as a representative $\underline{Q}_{x2}$ can be derived through the use of single-point targets.

Image Scale and Focal Length

Although changes in photographic scale can modify imaging geometry to a limited extent, there is basically a linear relationship between scale and precision. However, whereas an alteration in image scale may have only a scaling effect on $\underline{Q}_{x2}$, a change in focal length (retaining the same mean photographic scale) can influence the distribution of precision in the object space. As the focal length of the taking camera increases so the geometry of multi-ray intersections tends to become more homogeneous, thus leading to a reduction in the range of object point standard errors. Coupled with the enhancement of the homogeneity of object point precision, a further benefit of long focal length cameras is that they are less subject to the critical influence of film unflatness (e.g. KENEFICK, 1971). At the network design stage the latter of these two features is perhaps the most important to keep in mind, although the choice of focal length is most often limited by both camera availability and the physical layout of the survey site.

Self-Calibration Parameters

In recent years a considerable amount of research attention has been directed to the relationship of APs to network precision (e.g. GRÜN, 1978, 1980; BROWN, 1980; FRASER, 1980, 1982). Due to the numerous additional parameter models applied and the various special considerations that are warranted when APs are sub-block invariant, photo-invariant or a combination of these, it is difficult to establish general rules that will be effective in FOD. Nevertheless, a few characteristics of self-calibrating bundle adjustments warrant attention.

The first feature worth noting is that in the presence of high inter-correlations between APs, and strong projective coupling between APs and exterior orientation elements, object point precision and reliability are liable to be degraded. High correlation comes about through over-parameterization, e.g. polynomial terms of too high an order and the inclusion of APs which are not statistically significant. Care must be exercised in simulating networks which are to be adjusted by self-calibration. For example, if it required to examine the influence on $\underline{Q}_{x2}$ of carrying both interior orientation and decentering distortion parameters - which are often highly correlated - it is necessary to simulate an appropriate distortion pattern. In an examination of how well a distortion pattern can be modelled, the "error surface" must be input into the photogrammetric system.

As regards network geometry, it is well recognized that the determination of statistically significant APs is dependent on the provision of both a suitable imaging configuration and an adequate distribution of object points. For example, the recovery of the interior orientation parameters x_o, y_o and f in a "normal" network requires a target point array which is well distributed in three dimensions, and it is always enhanced by having non-constant (preferably mutually orthogonal) kappa rotations. As a rule, object point precision is not degraded so long as all APs are statistically significant.

SOD - THE WEIGHT PROBLEM

The weight problem or SOD involves the search for an optimal distribution of observational work, given both a network design and some ideal structure of $\underline{C}_x$. This problem is characterized by an unknown $\underline{P}$, and fixed $\underline{A}$ and $\underline{Q}_x$. In photogrammetric network design, a structure for the weight matrix of $\underline{P} = \sigma^{-2}\underline{I}$ is typically adopted. The quantity σ^2 is the global variance of image coordinate measurements. Thus, SOD involves only an optimization of the scalar value σ. There are effectively three methods available for increasing the precision of image coordinate observations: the use of a higher-precision comparator, multiple image coordinate measurements, and the use of multiple exposures, as outlined in the discussion on FOD. Since most high-precision photogrammetric surveys employ comparators with accuracies in the range of 1 - 2.5 μm there is typically not much flexibility afforded in the selection of a comparator as far as SOD is concerned.

Of the two remaining approaches the use of multiple exposures is, in the author's opinion, a more effective means of scaling σ to some required value. In theory, the effect on $\underline{Q}_{x2}$ of observing an image point k times is equivalent to a single observation of that point on each of k images taken at the same exposure station. However, the latter approach has one distinct advantage, that being that systematic error components which change from exposure to exposure (e.g. film deformation) are averaged over the k images. It is also possible, of course, to combine the two methods, e.g. multiple-readings on each of the multiple exposures.

TOD - THE DENSIFICATION PROBLEM

In light of the fact that object point precision is largely independent of target array density in networks with "strong" geometries, the densification problem does not seem to arise. Effectively, the densification problem is solved at the FOD stage, and TOD generally need not be separately considered in a photogrammetric network optimization.

DESIGN THROUGH SIMULATION

Computer simulation of non-topographic photogrammetric networks has been successfully employed in design optimization for some time. But the development of powerful minicomputers and graphics terminals has given a considerable boost to interactive network design, to the point where simulation and adjustment software packages are becoming commercially available. One such package, which is briefly discussed here, is the STARS system developed by Geodetic Services, Inc. (e.g. BROWN, 1982). The process of photogrammetric network design optimization through computer simulation can follow a number of approaches. One practical procedure is summarized by the flow diagram shown in Figure 1. Once the accuracy specifications have been established an observation and measuring scheme is adopted. This procedure may entail the selection of a particular camera or cameras for the survey, the comparator to be used, a first approximation of the imaging geometry, e.g. four-photo convergent configuration with scale 1 : S and all points appearing on all images.

The following equation can prove usual in this process:

$$\bar{\sigma}_c \simeq q\, S\sigma \qquad (7)$$

where S is the scale number, σ the image coordinate measurement standard error, and q a factor whose magnitude varies usually from about 0.5 to 1.2 for "strong" network designs. Equation 7 can be expected to yield a reasonable approximation of mean positioning accuracy. Appropriate values of the factor q are usually selected on the basis of results obtained in previous work. Alternatively, a coarse estimate for q could be based on the values obtained in the simulated networks considered in FRASER (1983).

Following the establishment of a general observation scheme the datum and configuration problems are addressed, and having completed a detailed ZOD and FOD the precision of the network is examined. If the specifications for an ideal $\underline{Q}_{x2}$ are met and/or if the network is deemed to be optimal, the design is complete. Should the simulated network fail the test of optimality with respect to the specified accuracy criteria, then the question of whether meeting specifications is a matter of scaling $\underline{Q}_{x2}$ should be asked. If such an approach is practicable, the SOD process (multiple exposures and/or multiple image coordinate measurements) can be followed until the accuracy objectives are obtained.

If the structure of $\underline{Q}_{x2}$ (e.g. its lack of homogeneity) causes the network to fail the test of optimality then the SOD is bypassed and either the network design is revised, principally through the FOD process, or the general observation and measuring scheme are completely redesigned. In practice this whole procedure can be carried out interactively at the computer terminal.

THE STARS SIMULATOR

The graphics-based network simulator developed at Geodetic Services, Inc. forms an integral part of STARS, a proprietary turnkey system for close-range photogrammetry. (STARS is an acronym for Simultaneous Triangulation And Resection System.) As well as incorporating the design optimization possibilities detailed in the previous sections, the STARS simulator also allows the planner to answer certain questions of a practical nature, e.g. whether all targets of interest can be seen from a particular camera station. This package facilitates the generation of trial data sets, for which an error

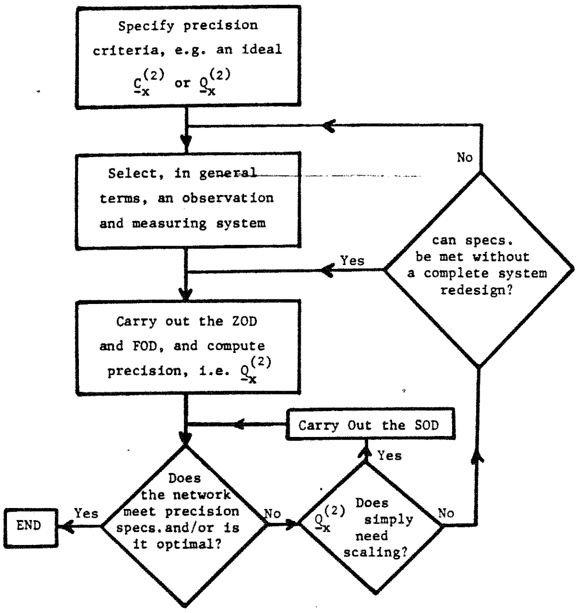

Fig. 1: Flow diagram for photogrammetric design optimization.

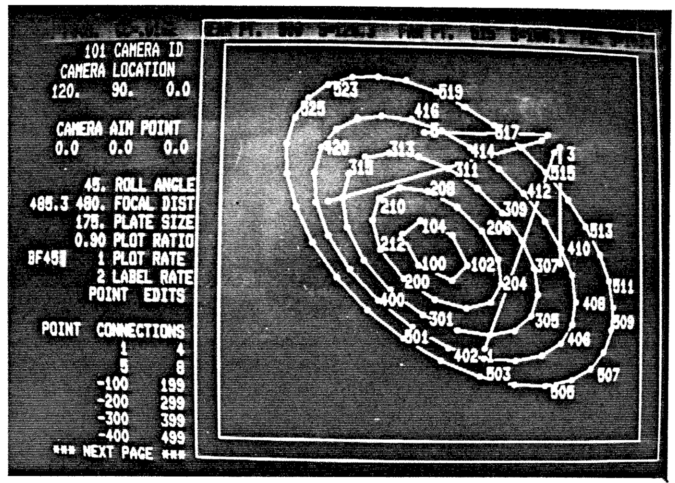

Fig. 2: Camera station view generated with the STARS simulator.

propagation is computed and network precision obtained via a self-calibrating bundle adjustment.

In commencing the simulation process, one first specifies the coordinates of object points of interest. Then, in a sequential fashion, each proposed camera station location is examined. The selected principal distance for the camera occupying that station is input, as is the frame format size. Following this the computer automatically optimizes the camera aim point (if required) and projects the set of targets provisionally seen from that camera station onto the terminal screen, as shown for example in Figure 2. Changes can be made interactively to the design, as warranted. Options include the ability to "zoom" the camera in and out along the pointing axis, automatic focussing and depth of field computation, and a camera roll capability. In addition, there are options available to specify viewing window size (to show points outside the frame format) and, for plot readiability, point and label plotting rates.

Once the camera setup has been established, image coordinate measuring standard errors are input and the object point positioning precision is computed. At this point, one is essentially at the first decision stage of the flow diagram shown in Figure 1. Based on whether the network meets the specified accuracy objectives, the planner can either modify the design through the simulator or stop if an optimal design has been obtained. It may even arise that the simulation will indicate that the desired accuracies cannot be attained under reasonable circumstances.

Through the simulation exercise a photogrammetric project can be comprehensively planned. As a further benefit, the STARS simulator is set up to be used essentially as a teaching tool such that non-photogrammetrists can quickly become proficient in photogrammetric project planning.

CONCLUDING REMARKS

This paper has dealt with design aspects of photogrammetric networks, and the interconnected processes of zero-, first-, second- and third-order design have been outlined. From the treatment of the different design classifications discussed, it should not be implied that photogrammetric network optimization amounts to a formal step-by-step procedure through ZOD, FOD and SOD. The flow diagram presented in Figure 1 describes one general scheme, but more often than not other factors such as previous experience and intuition will play a central role in network optimization. In any computer simulation, however, it is useful to keep in mind the general design characteristics discussed. As is demonstrated by the STARS simulator, a comprehensive CAD technique can be employed effectively in photogrammetric network design. Indeed, for perhaps the majority of high-precision industrial photogrammetric applications design through simulation becomes mandatory, and not just desirable.

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