ON-LINE TRIANGULATION PERFORMANCE OF THE NRC ANAPLOT

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ABSTRACT

The on-line triangulation software for the NRC Anaplot is designed to provide an efficient, quality controlled data acquisition system, eventually followed by an independent off-line block adjustment of any desired type. One of the main objectives is to maintain maximum control of the process and its reliability. This is achieved by adopting a consistent system of data banking, by an early computer control of real-time image positioning in a unique stereocomparator/plotter operating mode, by a systematically applied coordinate transfer/identification of tie points between models and strips, and by an interactive quality control of data by statistical testing and subsequent editing. The practical implementation results in a significant reduction of preparatory work, higher production efficiency and in an almost full elimination of gross errors before the final block adjustment is entered.

INTRODUCTION

The NRC Anaplot triangulation is designed as a simple bridging procedure consisting of a series of sequentially applied scale-constrained relative orientations, within individual strips of photographs. The model coordinates of tie points from previous models directly constrain the intersections of corresponding rays in new models, so allowing for a single-step checking of all internal geometric relations within individual models. Spatial transformations are then used to assess the fit of the strip with available ground control. A special strip-tying procedure provides additional tie points in lateral strip overlaps. The final block adjustment of any desired type is performed off-line, based on data banks established during the on-line process. In all operations, including the real-time routines, a three-step system of corrections is adopted which allows to distinguish four different levels of the coordinate definition: encoder readout - photograph - camera - ideal image. One of the main objectives is to maintain maximum control of the process and of its accuracy. The emphasis is placed on providing an early computer control of image positioning yielding a parallax-free optical stereomodel. This is implemented as soon as the minimum number of needed observations is collected and is automatically refined with each new observation entered. Measurements and computations are interrelated through a combined use of a stereocomparator and plotter mode of operation.

The early potential of the NRC Anaplot triangulation was described by Kratky (1979, 1980). In the last four years the system has been further developed and refined to provide a full, efficient service in a production environment. This paper provides an overview of its present functions with a particular emphasis on their logical structure and on the operator-computer interaction in the control of the process.

BASIC CONCEPTS

Main System Functions

The bridging function of the Anaplot is supported and greatly facilitated by a combination of some unique hardware and software features. They allow for a versatile use of manual or computer control of the real-time positioning operation applied either to the left or right photo stage, alternately considered to be dependent as the bridging proceeds. Essentially, there are three different controls of positioning operations as sketched in Figure 1. In the parallax mode, activated by a special footswitch, x- and y-parallaxes are generated and measured in the currently dependent picture. Both parallaxes are then applied together with the manual positioning of the old, independent photograph, thus typically representing the stereocomparator mode of operation. During the computer controlled positioning which provides the plotter mode of operation, only calculated values are applied.

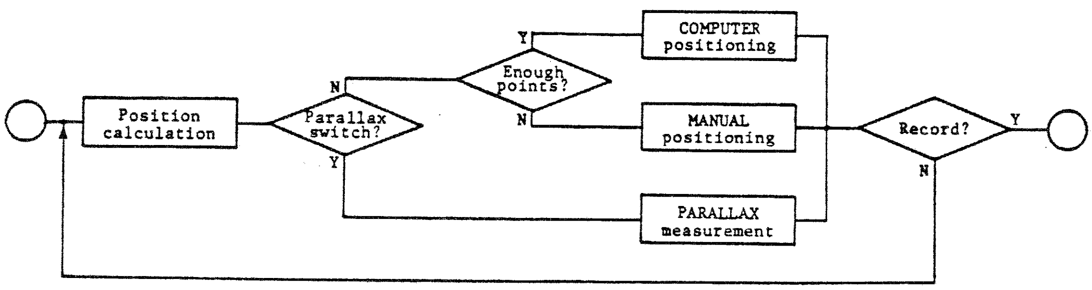

Fig. 1. Control of real-time positioning

Stereocomparator Mode. The manual control of measurements is achieved by handwheels X and Y which position the measuring marks in both photographs. By engaging the parallax switch the same handwheels operate in the parallax mode, transferring changes px and py to a single photograph only, either left or right, depending on the status of bridging. A standard footwheel Z is a substitute for the px operation and its change is also projected to a single picture. The function of handwheels can be assumed by a joystick, which enables a single-hand fast planimetric positioning. From the operational point of view the Anaplot is here used as a stereocomparator.

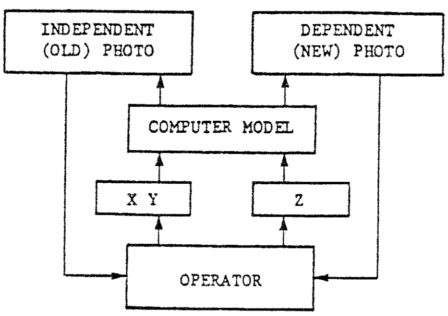

Fig. 2 Basic real-time positioning control

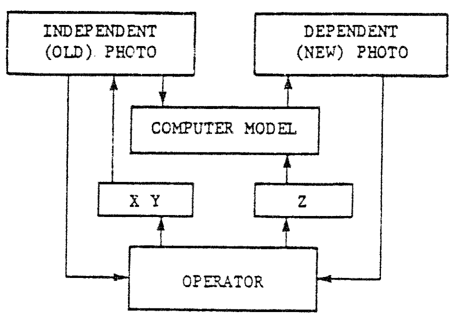

Fig. 3 Real-time positioning control in bridging

Plotter Mode. The operation is computer-controlled by a real-time positioning program. The original basic form of this program (Jaksic, 1979) used in single model operations, interprets input values X, Y, Z as model coordiantes and the computer calculates corresponding projections in both generally oriented photographs, which are then accurately servo-positioned. This is sketched in Figure 2. The modified bridging version of the real-time positioning program conveys the illusion of a stereocomparator operation by transferring X, Y values directly to the independent photograph. This is necessary in order to establish the given positions of tie points measured in preceding models. A given value Z entered from the footwheel, and another projection into the dependent photograph concludes the loop as sketched in Figure 3.

Combined Mode of Operation. In the initial stage of the orientation, i.e. up to the fifth measured point in the first model and up to the fourth point in subsequent models, the computer control is bypassed. Handwheel changes are effectively transferred to both photographs or, with the parallax foot switch engaged, as parallaxes px, py only to the dependent photograph. Any change of Z entered from the footwheel is interpreted and entered as a px-parallax scaled with the use of the proper base-to-height ratio.

Once the minimum number of measured points is reached, computed parameters of the orientation are used in the real-time computer control of the dependent photograph, yielding a parallax-free optical stereomodel when changing the X, Y, Z input. It should be noted, that in agreement with Figure 3, a Z-motion would not affect the position of the measuring mark in the old picture and it is displayed as a px-parallax only in the dependent picture. The model point is shifted along the projected ray rather than in the vertical direction. The parallax foot switch, when engaged, overrides the computer control so that changes px, py are transferred directly to the dependent photograph at any time. Simultaneously, the current value of Z is updated for the effect of the introduced px-parallax. When the parallax switch is released the floating mark retains its Z-position in the optical stereomodel, but the introduced py-refinement is immediately lost and replaced by the computer preferred value y in the controlled dependent photograph. Any py-refinements needed must, therefore, be recorded with the parallax foot switch engaged. After any new recording the current orientation parameters are automatically updated in a fraction of a second and the computer control always reflects the effect of the new measurement. This type of procedure enables the operator to perform all remaining measurements in the controlled model space, not by appending additional observations to a completed model, but in a dynamic procedure which repeatedly refines the definition of the model with each new point entered.

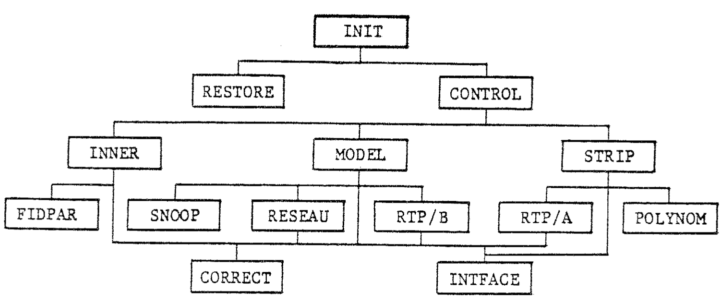

Fig. 4 Program hierarchy

Program Structure

The structure of all Anaplot operations is modular; one main program (INIT) initializes and terminates the session, while numerous independent subroutines are organized at several levels as indicated in Figure 4. Only the most important functions discussed in this paper are shown here. The connecting lines represent subroutine calls (directed only down with a return up to the calling module). Most of the names are mnemonic. The CONTROL module provides an access to the major operational phases, which are: inner orientation of photographs, model formation and strip transformation. FIDPAR is a module to determine parameters of fiducial transformation, SNOOP is used for gross error detection, RESEAU for optional measurements on réseau marks and POLYNOM performs polynomial transformation. Names RTP/A, RTP/B stand for the real-time positioning routines in their standard or bridging form, respectively. The lowest level of subroutines represents the basic utility functions for correcting photo coordinates and servicing the interface registers and switches.

OPERATIONAL FEATURES

Control of the Process

The operator's interaction is needed to specify, control and modify the procedures. It is implemented either in a conversational mode from the computer video terminal or through a series of software controlled console switches. A total of six master switches controls the choice of major operational phases of the process. In the flowcharts appended to this paper they are denoted as P1, P2, ...P6. Another set of momentary pulse switches A1, A2, ...A5 initiate or stop specific actions within the above phases. Additional four switches M1, M2... M4 are latched and their alternate on/off state defines the optional mode of current operations.

In the flowcharts, all blocks with some interactive implication are differentiated from blocks representing purely computer controlled operations and decision making. For any video terminal input resulting either from a conversation or menu selection, the left side of relevant flowchart blocks is graphically accentuated by heavy lines. In turn, any operations and decisions involving Anaplot hardware functions are marked by blocks with accentuated lines on their right hand sides. This applies, e.g., to measurement and positioning cycles, as well as to any operations on control switches.

Main Program. Appendix A-1 contains a flowchart representing the logical structure of the main program. Through conversation, answers are provided to set control flags, to assign needed attributes and to define other useful input. The meaning of flags and attributes is explained in the legend of the Appendix.

The first section takes care of the conditions for model restoration. In the second section, depending on the already selected attribute RESET, the long input of values to be specified is bypassed if one is resuming a previously interrupted Anaplot operation. The lower section of the flowchart illustrates the main control of triangulation operations. In an indefinite loop the P-switches are interrogated and any of the three modules (INNER, MODEL, STRIP) is entered only when P1, P2 or P4, respectively, is depressed. Switch P6 causes a temporary or final program termination, after important data are stored on disk.

Inner Orientation. The flowchart in Appendix A-2 describes control during the inner orientation of photographs. In the first phase the operator identifies the photographs and determines if fiducial transformation is needed or supported by available information. If the answer is negative the fiducial pattern attribute is entered, which allows for an automatic stage positioning from fiducial to fiducial. When fiducial transformation is requested, the available information table is loaded from disk. From the format and number of records in this table the computer recognizes automatically which type of transformation is feasible and a corresponding attribude TRFM is assigned. The first hardware related function is the approximate centration of photographs followed by indefinite measurement cycles, interrupted by switch A1 to record fiducial coordinates or, for a non-standard pattern, by switch A4 to terminate the measurement cycle. Depending on the transformation flag (TRFM-F) and attribute (TRFM) a suitable transformation is computer selected. Affine transformation (with three parameters) is standard when four calibrated fiducials are available, whereas bilinear transformation (with four parameters) is applied for photos with more than four fiducials. When only calibrated distances are computer detected in the fiducial information, a simple transformation (with two parameters) to correct for film shrinkage is implemented.

Model Formation. The operational control during the main triangulation phase is flowcharted in Appendix A-3. Here again, an indefinite program loop allows for measurements in a real-time positioning mode RTP/B (see Figures 1 and 3), interrupted for recording when action switch A1 is depressed, or terminated with action switch A4 when driving pattern is completed. Other action switches support ancillary functions, such as the display of current orientation parameters (A2), visiting of other points (A3) or the cancellation of the last point (A5). When A4 is applied two times in a sequence data snooping and display is activated. The computer controlled recording and computations are eventually followed by data editing. The operator's interaction here is conversational and allows for three functions: ADD, REPLACE and DELETE. When editing is finished and mode switch M4 engaged the RESEAU subroutine is called which facilitates auxiliary measurement on réseau marks. Before all measured information is finally stored in data banks a mandatory check on a suitable reference point makes it possible to discover potential coordinate encoder malfunction during the model orientation, so that the whole process MODEL can be repeated.

Tie Point Identification and Transfer

Ties between Models. In NRC triangulations the tie points within a single strip are selected during the operations, without any preliminary identification, marking and numbering. The tie points in the following models are then identified by their photo coordinates in the common photograph. As long as the number and position of required tie points between models is standard, the computer also takes care of automatically assigning them unique identification numbers. These tie points do not even have to be well defined in planimetry, as long as their parallaxes can be measured accurately. In order to measure a tie point in the current model the computer positions the old photograph using the coordinates recorded from the previous model, and blocks any unwanted manual displacement from this given position until the stereomeasurement in the new photograph and the recording is completed.

If it happens that the tie point position in the new model is established with some minute discrepancies caused by an imperfect function of the servohardware, the displacement is software detected and automatically corrected in both pictures so that the coordinate fit in the old photograph is absolutely enforced to a single micrometre. The same type of correction is also applied if the point definition in the new photograph is accidentally affected by a scratch or other local imperfection in the photo emulsion. In this instance, the operator can release the computer position-holding function by mode switch M3 and move the flating mark as needed to do the measurements in the nearest vicinity of the flaw. Upon recording of coordinates the displacement is automatically compensated by software.

Ties between Strips. The pre-triangulation identification and marking of lateral tie points is not necessary for the NRC on-line triangulation as the ties between adjacent strips are secured by their coordinate transfer. One can form stereopairs for this purpose from photogrpahs belonging to adjacent strips, with a rotated stereobase. This approach results in an introduction of additional cross pairs to be measured within the limited side overlap of strips. For the sidelap smaller than 50% the number of measured points per cross pair and their configuration are obviously not adequate to support accurate photogrammetric computations. Consequently, the operation is carried out in a stereocomparator mode, without any real-time computer control of positioning. The cross-tying operation takes advantage of the available data banks built up during the bridging of individual strips. The operation proceeds by forming cross pairs from laterally adjacent photographs. This is done at the beginning and the end of strips, as well as at suitable intervals inbetween. Since every cross pair spans over two bases (2b) in the strip direction, the traverses repeated at 3b intervals, i.e. for every third photograph, will provide a continuous sequence of lateral tie points between strips:

```
|x x x|x x x|x x x|
   2     5     8
```

To generate lateral strip connection with groups of tie points separated by gaps of four bases requires traversing for every sixth photograph:

```
|x x x| . . . |x x x|
   2             8
```

e.g., in a block with 21 photographs per strip the cross-tying procedure will be applied four times. The photographs are placed in the Anaplot stages rotated by 90° so as to use stereoperception in the sidelaps. The alternate mode of changing photographs in left/right stages speeds up the procedure as in bridging.

The procedure is illustrated by a flowchart and computer listing in Appendix B. After loading a pair of rotated photographs and entering their identification numbers, the banks for fiducial coordinates are searched, appropriate values identified and extracted. The originally measured and now retrieved coordinates of fiducial marks represent a given set of values into which the newly measured fiducial coordinates must be transformed in the process of inner orientation. The set of transformation parameters derived in the process will control an auxiliary transformation applied to all subsequent measurements to convert them into the original coordinate system of photographs stored in the data banks; the fit is within the accuracy of measurements on fiducials. Estimated base component values define the cross pair overlap within which the search for available lateral tie points is limited. The measurement process can be aborted at any time by switch A5 and the point in question is then skipped. Before recording, the measurement coordinates are corrected for system errors, rotated and transformed. Additional tie points may be chosen and measured with no relation to the data banks. As a result of these operations a new file of lateral tie points is gradually built up for the use in the final block adjustment.

Data Banking System

A suitable organization of collected data is not only important for the final off-line processing and block adjustment, but it is also crucial for the support of certain auxiliary functions which eventually make on-line triangulation so efficient. Several important data files are continuously generated, stored and updated on disk during all operations. They are later used as data banks to search for and retrieve the already available information. In the progress of triangulation data banks are expanded by appending new information to existing files. The data banks are accumulated and preserved for as long as needed for the triangulation block in progress and are cleared only by a request combined with a positive reconfirmation. An appropriate reorganization of data banks is implemented by a special program, after new measurements are entered in a restoration of an old model or part of the strip. The files are specialized to store independently photo and model coordinates of all points measured in the process of bridging, measured coordinates of fiducial marks, transformation parameters derived in inner orientation, orientation elements of all photographs involved and photo coordinates of lateral tie points.

Quality Control

An efficient quality control of observed data in every MODEL solution is implemented by applying the data snooping technique for gross error detection (Kratky, El-Hakim, 1983). Values of redundancy numbers and standardized residuals are computed for each observation, a rigorous statistical test is applied and the results displayed. Weak points indicated by the test are remeasured and the test is repeated if necessary in a "trial and error" approach, which is extremely well suited for an on-line environment. The testing is accessed from the measurement section of the MODEL routine by manually activating switch A4 twice in a sequence (see flowchart in Appendix A-3).

In this regard two important aspects must be considered - the accuracy of collected data and the efficiency of used procedures. The efficiency is not only judged by the time needed to perform the operations, but also by the intrinsic reliability of data. The on-line calculations are always applied to data of limited volume and are not so much important for the final, usually independent, block adjustments, as they are for the crucial function of quality control. One should take great care that statistical testing is not too adversely affected by the limitations of the on-line geometric configuration. This will ultimately be improved in the final, simultaneous processing of data, but then statistical tests are much more difficult to run. It is, therefore, important to consider suitable point configurations which guarantee high reliability of statistical testing at the time of the data collection and editing, rather than to try to reach the highest possible accuracy of intermediate numerical solutions.

Numerous practical experiments and on-line simulations showed that the critical areas for the testing reliability are in model corners. It appears to be very efficient to strengthen the stability by doubling points in these areas. A configuration of 13 points (nine standard positions with four doubled corners) provides five tie points between models and is considered best for a practical routine use.

Control Point Checking

The bridging of a strip progresses in repeated sequences of inner orientation and scale constrained relative orientation. It is based on a scale chosen close to that of photographs and the recorded model coordinates are expressed in a uniform strip coordinate system. From the operational point of view, there are no specific requirements as to the number or location of ground control points. They are identified as such, and measured whenever they become available in any model of the strip. Although the bridging procedure is not dependent on the inclusion of their ground coordinates in the reconstruction of the strip, it is useful not to wait with checking the triangulation fit on control points until the whole strip is finished. Instead, the NRC software offers an intermediate polynomial transformation of any part of the strip currently available, whenever it is geometrically justified.

The transformation can be applied after any particular model of the strip is completed (see module STRIP in Figure 4). The request is entered by activating switch P4, as shown in the control section of INIT in Appendix A-1. The logical structure of the procedure is presented in the flowchart of Appendix A-4. In a conversational mode, the operator specifies the identification numbers of control points already measured in the strip. Corresponding coordinates needed for the transformation are automatically extracted from the model coordinate bank and from the available ground control point file, and they are stored for this and any subsequent use in a disk resident auxiliary work file. Because of this arrangement, there is no upper limit set for the number of points used in the transformation.

Similarity transformation is applied first and coordinate discrepancies on control points are displayed on the terminal together with the corresponding RMS errors characterizing the x, y, z fit. In an editing procedure more points may be called in or some points can be eliminated from the transformation. Depending on the level of the ground control support and on the length of the so far processed strip, the operator can opt for additional polynomial transformation of a specified degree, independently for planimetry and for elevations.

The planimetric transformation is handled by conformal polynomials of up to the 3° and its formulation is based on the use of complex numbers. The polynomial transformation of elevations is implemented with the use of the following coefficients

$$(1 \quad x \quad y \quad x^2 \quad xy \quad x^3 \quad x^2y),$$

associated with five or seven parameters in polynomial transformation of 2° or 3°, respectively.

Both the similarity and polynomial transformations are computer run in near-real-time and the results are displayed for an analysis within a few seconds. The transformation is considered to be an auxiliary operation for checking purposes, displayed only on the video terminal or later printed. The results are not permanently stored and do not change, in any way, all the recorded data from the strip formation.

If the coordinate fit is satisfactory the strip is continued by bridging over the following models until new control points are available. Then the transformation is applied again. This time all the control points previously chosen are automatically available and the operator identifies only new control points to run another transformation of his choice. When a gross discrepancy is discovered an identification error is the most likely cause. If the suspected point happens to be in the current model the remeasurement is easy. The program is set in a way that one can combine coordinates retrieved from model banks with model coordinates directly measured in the current, physically still available model. If mode switch M4 is engaged (see Appendix A-4) the real-time positioning routine RTP/A starts its indefinite cycle interrupted only by action switches A1 or A4 to either record the measured model coordinates or to terminate the cycle, respectively. Computations are then rerun and the old model point eventually deleted. In case the suspected control point is located in some of the preceding models, the bridging of the strip is temporarily suspended. The faulty model must be reset from data banks in a procedure described in the following section, and the control point in question checked. After the point is checked or remeasured, the operator can either continue from this model on and repeat the remaining part of the strip, or return to the last model, reset it and continue from there with a minimum loss of time.

Model Restoration and Reset

The first section of the flowchart in Appendix A-1 indicates the initial conversation in which the operator decides on the type of operation by properly defining the RESET attribute which then controls some of the subsequent functions.

Restoration of the Last Model. In any production environment it is often necessary to suspend the operation temporarily and continue later with no loss of data and without the need to repeat any of the measurements. The photographs must remain in their stages during the interruption and the measuring mark must be set on a well defined optical detail or its position secured by disabling the manual control elements. Then it is only necessary to store all needed information in an auxiliary file for later restoration of the model. Information needed for this purpose includes the contents of all Anaplot registers, all working variables and arrays representing the conditions of the current work or its status at the time of interruption and all orientation parameters. The generated storage file is disk resident and its contents can later be read back to the memory or transferred to Anaplot registers as needed to establish the identical physical and numerical situation frozen at interruption time.

Reset of an Old Model. Another situation arises when there is a need to go back and reset a stereomodel from photographs which were already physically removed from Anaplot photo stages. This is usually done for the purpose of checking measurements of a control point suspected of a misidentification. In this instance, it is necessary to use the data banks so far collected during the preceding triangulation operations. A special resetting program searches through available data files for given photo numbers and retrieves previously recorded information important for the reset. Additional information on conditions of the original solution is reentered manually from the computer terminal. A new inner orientation of both photographs involved represents the only measurement procedure needed in the reset. The new set of measured fiducial coordinates is fitted with the corresponding set of previously recorded and retrieved coordinates by affine or bilinear transformation. The derived transformation parameters are then capable of relating the new physical situation with the old one. The logical structure of the operation is sketched in the flowchart of Appendix A-2. The restored optical and numerical models are identifical with the previous ones within the range of a few micrometres, as characterized by discrepancies in the transformation fit on fiducial marks after the new inner orientation. The new model can be checked and remeasurements carried out as needed. In most instances, the misidentification is corrected and new bridging of the remaining photographs in the strip is not necessary.

CONCLUSIONS

By choosing tie points during the measurement process, one avoids problems otherwise associated with their identification and drastically reduces the time necessary for preparatory triangulation work. The tedious and time consuming selection of the points in image overlaps becomes unnecessary. Also redundant is the point transfer by mechanical marking of photographs in special devices and manual point numbering. The NRC on-line triangulation represents a fast and efficient procedure with an adequate checking power to produce accurate data practically free of gross errors and blunders. Thus, it greatly simplifies the ultimate off-line block adjustment of data.

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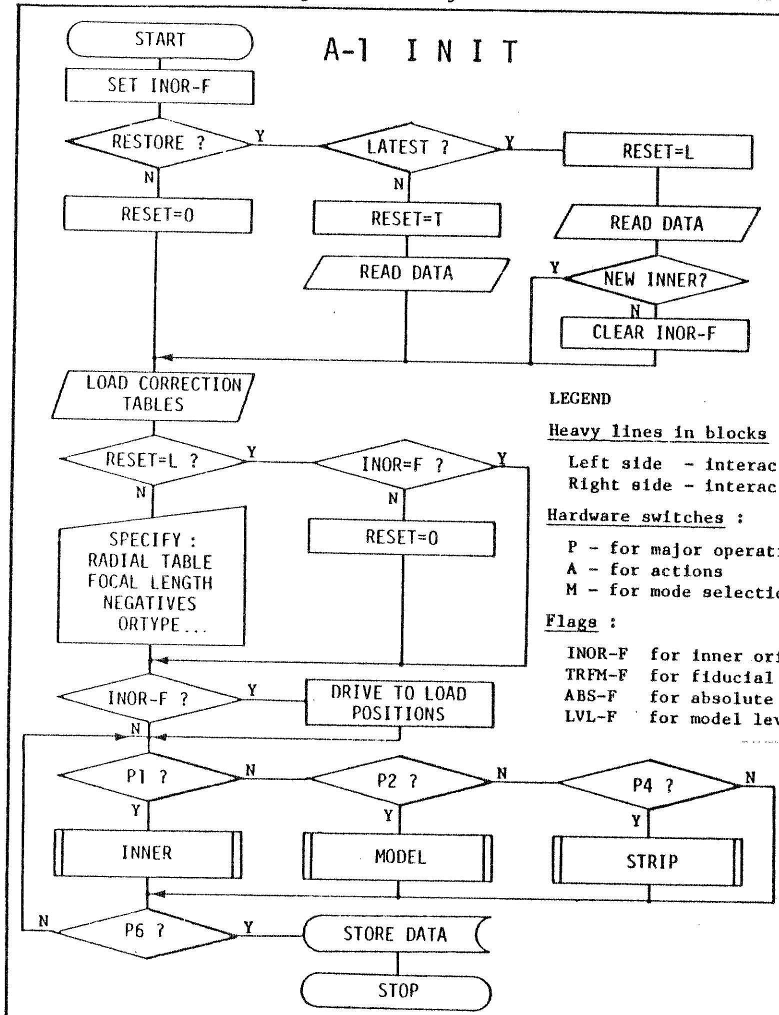
APPENDIX A-1-2 Operator system interaction in NRC triangulation



LEGEND

Heavy lines in blocks :

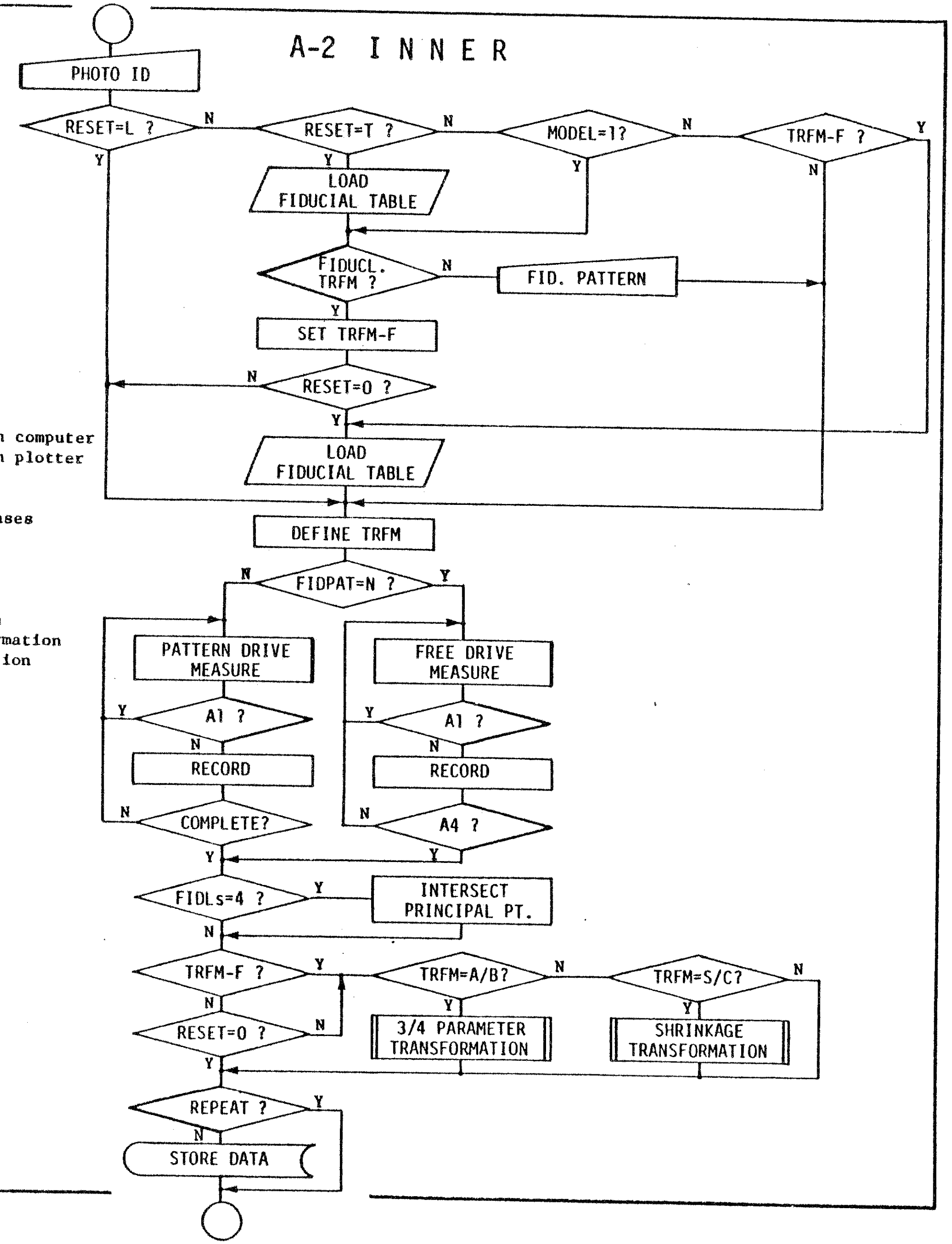
Left side - interaction with computer
Right side - interaction with plotter

Hardware switches :

P - for major operational phases
A - for actions
M - for mode selection

Flags :

INOR-F for inner orientation
TRFM-F for fiducial transformation
ABS-F for absolute orientation
LVL-F for model levelling



Attributes :

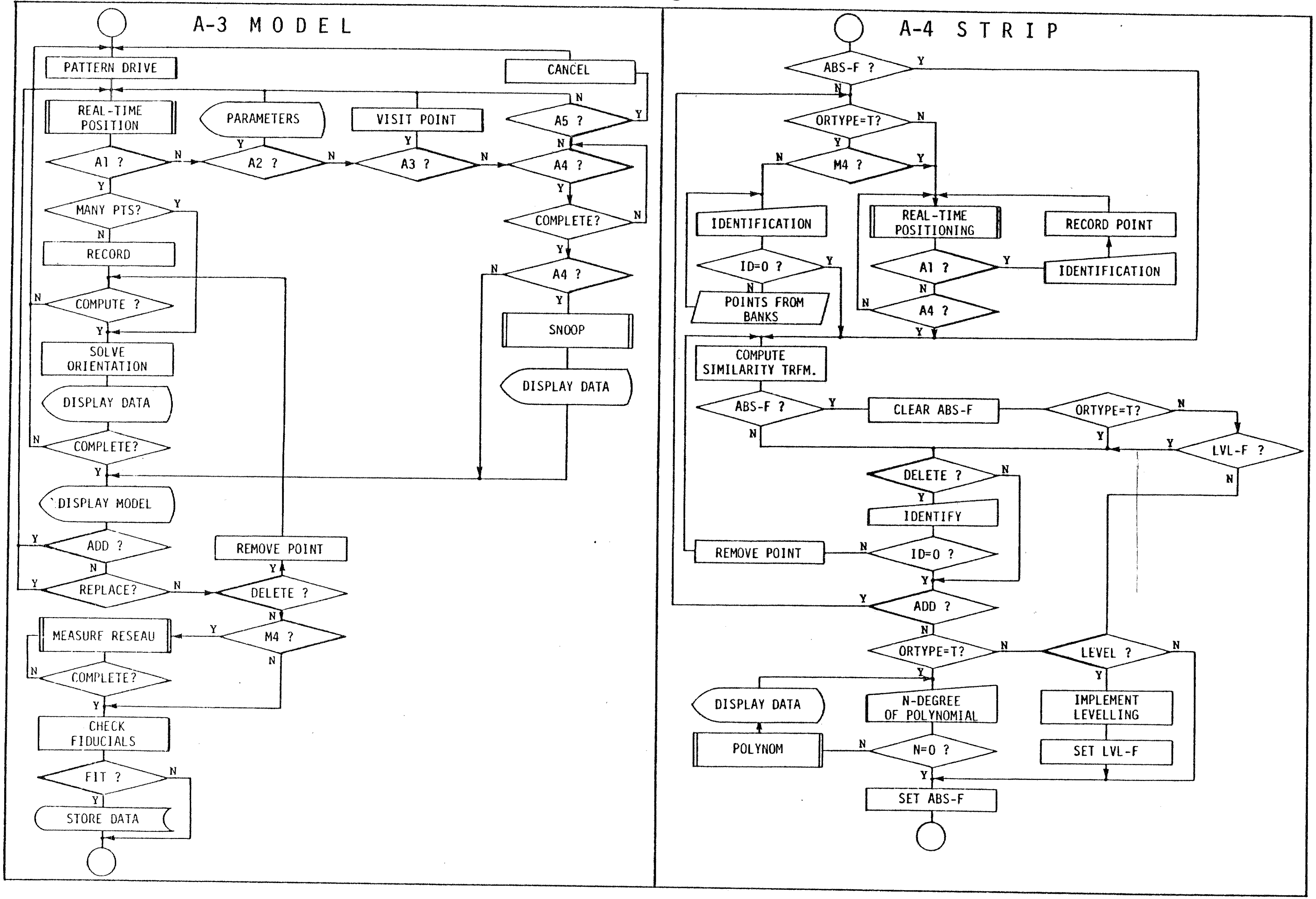
RESET (O/L/T) restoration mode
- 0 - no reset
- L - latest model
- T - model from triangution files

ORTYPE (I/T) orientation type
- I - independent model
- T - triangulation model

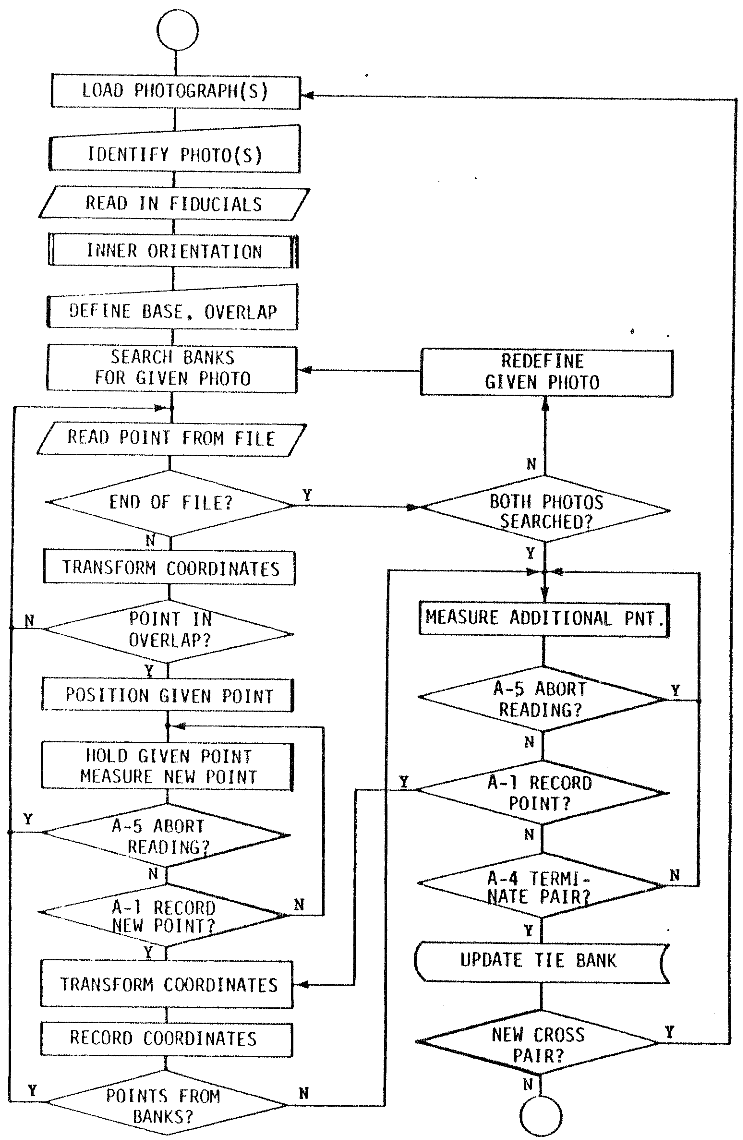
FIDPAT (C/S/N) fiducial pattern
- C - corner fiducials
- S - side fiducials
- N - non-standard fiducials

TRFM (A/B/C/S) transformation type
- A - affine
- B - billinear
- C - shrinkage from corner fiducials
- S - shrinkage from side fiducials

APPENDIX A-3-4 Operator-system interaction in NRC triangulation



Appendix B Operator-system interaction in NRC strip tying




```
*** TIE POINT TRANSFER BETWEEN STRIPS ***          21-FEB-84  14:43:30

OPEN NEW TIE BANKS? Y

NEGATIVES? N

NUMBER OF REPEATS =      1

LOAD PHOTOGRAPHS, THEN PUSH MS1!

PHOTO # =     87

PHOTO # =    114

CENTER BOTH PHOTOS!

TRANSFORMATION FIT FOR PHOTO #  87
DX      -0.      0.     -0.      0.
DY       8.     -8.      8.     -8.

TRANSFORMATION FIT FOR PHOTO # 114
DX      -3.      3.     -3.      3.
DY       0.     -0.      0.     -0.

REPEAT ORIENTATION? N

ENTER BASE COMPONENTS BX, BY:          60.        80.

FROM    89   87 :
        87  114   872     1.138    -0.575   -76.996    56.505
        87  114   873    -0.511   -70.449   -76.992   -12.232
FROM    85   87 :
        87  114   852   100.412    -2.388    19.906    58.632
        87  114   853
        87  114   146    25.908   -82.962   -52.241   -22.518
        87  114     5    16.902   -41.516   -62.242    18.419
FROM   112  114 :
        87  114  1121   -12.666    26.127   -91.204    81.839
        87  114  1122
        87  114  1141
        87  114  1142    81.076   -61.500     2.111     0.604
        87  114   336    30.649   -56.073   -47.588     3.928
        87  114   337    34.690    -3.885   -44.923    55.060

MEASURE ADDITIONAL POINTS!
ID =     77
        87  114    77    35.261   -18.712   -44.393    41.014

ANOTHER PAIR?

*** TIE TRANSFER COMPLETE ***                                      14:55:52
```