DIGITAL COMPARATOR CORRELATOR SYSTEM

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ABSTRACT

This paper describes the Digital Comparator Correlator System (DCCS), developed by Helava Associates Incorporated (HAI) for automatic selection and measurement of tie points for block triangulation. The comparator part of the system is a monocomparator equipped with a calibrated solid-state area sensor. It is used to extract digitized patches from aerial photographs, to be used as inputs to point selection and correlation. Because the patches can be stored digitally for later use, the monocomparator becomes, in effect, an N-stage comparator. The selection and correlation processes are automatic and fully digital. Point selection is based on outputs of an interest operator. Simultaneous, mathematically-rigorous multi-image correlation is performed on tie points using least squares correlation (LSC). Standard deviations of correlated image coordinates are on the order of 0.01 pixel, while the RMS of image residuals after ray intersection are on the order of 0.1 pixel. The latter number indicates that the correlator has found conjugate image details with that accuracy. The system includes algorithms for automatic positioning and recapturing of tie points at standard locations, as well as an optional direct link to a block triangulation program (GIANT). While the DCCS is intended for triangulation measurement, in a wider sense it is the first representative of a new generation of photogrammetric instruments.

INTRODUCTION

Four methods are commonly used to define tie points for block triangulation: (1) Targets are placed on ground at locations suitable for tie points. This method gives good results, but distribution and maintenance of targets can be very expensive; (2) Points are transferred using special point transfer devices and marked on the photographs for later measurement in a comparator. This method usually entails significant loss of accuracy; (3) Natural points are transferred by using hand made sketches as point identifiers, often supplemented by written descriptions. This method is rather time consuming; (4) Analytical plotters or computer-supported comparators are used to identify and transfer natural points. This method is quite efficient, and becoming widely used. However, the operator still has to select, transfer, and measure the points.

Currently available digital techniques open up new possibilities. One attractive possibility is to digitize patches of images at intended tie point locations. These patches can be then be stored digitally and used as inputs to digital correlation. To achieve required accuracies, the patch extraction system must be essentially a comparator. A monocomparator will suffice, since the patch storage capability makes it an N-stage comparator.

The "point" can be defined by its pixel coordinates on one of the patches; with its conjugates on the other patches found by correlation. In this process Least Squares Correlation (LSC) makes a unique contribution: It provides the means for simultaneous multi-image correlation, thus completing the N-stage comparator paradigm. This contribution is significant, because until the advent of LSC, photogrammetry has not had a mathematically tractable method of point transfer between multiple images. Automatic definition and correlation of tie points eliminates time consuming point selection, transfer, and measurement by human operator, thus resulting in an extremely efficient method of tie point measurement.

This paper begins with a description of the hardware embodiment of the Digital Comparator Correlator System (DCCS). The remainder of the paper deals with its "mental" capabilities residing in its software. We first describe the method of automatic tie point selection incorporated into the system. Hierarchical Relaxation Correlation (HRC) for image pull-in, and Least Squares Correlation LSC) for multi-image measurement are then discussed, with emphasis on the versions used in the DCCS. We then present an outline of the operating procedure designed for the DCCS and intended to be "operationally intelligent". Various optional capabilities, such as blunder detection schemes, are also discussed. Finally, the growth potential of the system and directions of further developments are briefly sketched.

DIGITAL COMPARATOR CORRELATOR SYSTEM (DCCS)

The Digital Comparator Correlator System consists of three main hardware components: a monocomparator/image sensor, display/control console, and a controller/correlator. Figure 1 is a photograph of the system; a block diagram is shown in Figure 2. Less visible, but probably more important, is the system software. It consists of standard operating software provided by the computer manufacturer, and a large body of control, correlation, and automation software developed by HAI.

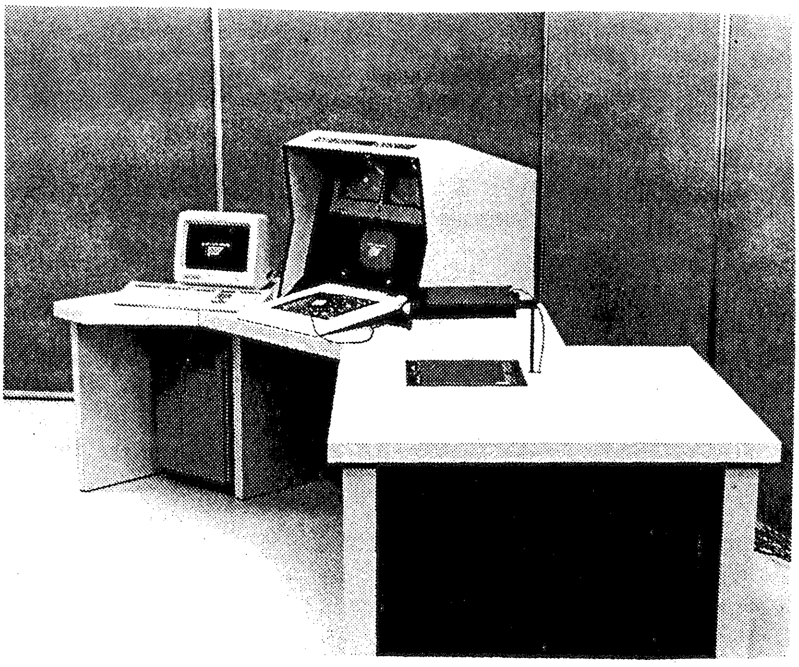

Figure 1 - Digital Comparator Correlator System (DCCS)

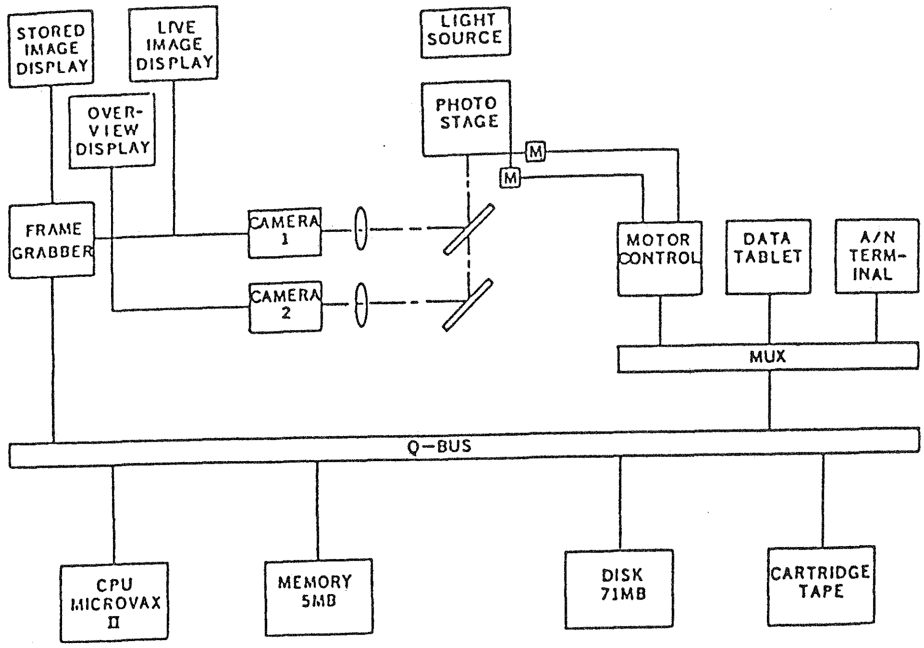

Figure 2 - DCCS Block Diagram

The monocomparator is a sturdy, industrial type xy-stage, equipped with linear encoders and DC-servo motors. The stage carries one, or optionally two, CCD-sensors and associated optics for image digitizing. The comparator is built inside of a table, and the sensors "see" the input photograph through a window in the table top. The photograph remains stationary throughout the mensuration process. This arrangements permits easy incorporation of a film transport mechanism, if desired.

The nominal pixel size of the standard sensor is 20x20 micrometers. This pixel size has been determined to be optimal operationally and economically. The exact pixel dimensions are derived by an automatic sensor calibration included in the system. The second (optional) sensor channel may be equipped with zoom or overview optics. Typical pixel size for overview is 60x60 micrometers. Optionally, other pixel sizes can be provided for the standard sensor, but would have serious system-level consequences. Such options should be considered for research purposes only.

The stage motions are actuated by computer-controlled servos. A high-performance motion controller was designed by HAI, specifically for the DCCS. The maximum speed of the motions is 40 millimeters per second. The resolution of the comparator is 1 micrometer, with an accuracy of 2 to 3 micrometers.

The display/control console is mounted on a specially designed table beside the comparator. The comparator unit can be placed on either side of the console. The console has three CRT displays, and a data tablet with a 12-button cursor. The control computer fits underneath the console.

Two CRT screens are side by side at the eye level of the operator. They are used to display high resolution images, either directly from the digitizer, or retrieved from digital storage. It would be possible to view the images stereoscopically with the addition of a simple clip-on stereoscope, but inherently there is little need for stereo viewing in normal operation of the system. The measuring mark is injected on the image in the digital domain, thus avoiding measurement errors due to CRT distortions.

The optional third CRT display is placed below the main displays. It is used to display an overview of the image being measured, if the overview option is included. The overview is sometimes desirable in locating points of interest, since the overview covers approximately 30x30 millimeters on the photograph.

Alphanumeric information needed to control the system is introduced via standard CRT-terminal mounted beside the console. Menus and graphics to assist in operation of the system appear on the screen of this terminal.
The data tablet provides most of the controls needed in real time to operate the system.

The data tablet cursor can be used to impart movements under manual control to the image being digitized. Three modes are available: slow incremental, fast incremental, and absolute. Slow incremental has a resolution of one micrometer on the image and is used to perform fine pointing, if needed. The fast incremental permits rapid movement from point to point under continuous manual control. The absolute mode executes fast slew motions under computer control. It can be used independently, or it can be oriented to the current photograph being measured. In this process, a print of the photograph being measured is mounted on the data tablet, and the operator uses the cursor to identify two points as instructed on the menu. The system then performs the orientation between the print on the data tablet and the photograph on the digitizing window. As a result, the cursor can be used to indicate a point of interest on the print and the computer will drive the sensor to that point.

The manual movement modes are selected by pushing an appropriate buttons on the cursor. The remaining nine buttons on the cursor are used for functions such as accepting and rejecting a measurement, selecting manual, semiautomatic, or automatic mode, toggling between dark and bright cursers; ordering image capture, jumping to a break function; etc. These cover essentially all real-time situations. In a properly organized production run, entries from the terminal keyboard are needed only when a new photograph is placed on the digitizing window.

The controller/correlator is an enhanced MicroVAX II. The primary enhancements are a frame grabber, a large Winchester disk, and a servo control interface. The microcomputer is the heart of the system. It reads the data tablet inputs and data from the linear encoders, keeps track of coordinates and operator actions, manages image grabbing and filing, implements point selection logic functions, and executes the correlation algorithms and other key functions of the system, including block triangulation using the GIANT program.

The hardware discussed above represents the physical embodiment of the system. Its "mental" realization is in its software, crucial to its performance, but nearly impossible to describe in a way that does justice to the "ingenuity" embedded in the software. For this reason, what follows is an attempt to describe what the software does, without trying to explain how it does it.

PLANNING ALGORITHM

Planning of triangulation measurements can be time consuming and costly, particularly when the points must be pre-identified and marked on the photographs. However, thanks to modern navigation aids, at least the blocks to be triangulated are often very regular. The DCCS has a planning algorithm that makes use of this regular structure of blocks. Inputs to the algorithm include the forward and side overlaps and the desired point pattern. The algorithm estimates point positions and transform parameters from photograph to photograph. It then corrects these estimates adaptively on the basis of any measurements made on the photograph. As a result, the algorithm is capable of driving rather accurately to points measured on preceding photographs, and predicting valid locations for new tie points, both along and across strips. In a recommended (default) mode, the algorithm also automatically assigns photograph and point numbers to be recorded in the photo coordinate file, although the operator can override this numbering system at any time, if he so desires.

POINT SELECTION

Selection and transfer of tie points by the operator adds significantly to cost of aerial triangulation. The DCCS overcomes this cost burden by making an automatic selection of tie points. In so doing, however, it encounters two interesting problems of its own: <u>One</u>, how to find a point with qualities that assure excellent correlation accuracy, and <u>two</u>, how to develop pass points for analog instruments, which are still in wide use but incapable of making full use of numerical orientation data.

A solution to the first problem implies analysis of the image content to determine a correlation "figure-of-merit". Several "interest operators" purported to accomplish this have been suggested. However, the problem is difficult. The success of the final ray intersection in triangulation is more a function of "conjugacy" than "correlation". While HAI has found conjugacy analysis rather successful in special applications, the techniques involved are too elaborate (i.e., too costly) for the DCCS. Therefore, the Förstner interest operator [1] was selected for use in the DCCS. Its performance has been found quite satisfactory.

The solution to the problem of providing pass points for analog instruments is to provide the ability to measure points that have been marked by drill holes or in similar ways. It is recommended for improved accuracy that tie points be selected and measured normally from image detail, and the drill holes be measured as auxiliary points that are not included in the triangulation, but are intersected after the adjustment. A special correlation technique, that essentially ignores the holes, is used to measure these auxiliary points.

"PULL-IN" CORRELATION

Correlation processes are key elements in the performance of the DCCS. Two correlation approaches are used, one to accomplish a "pull-in", the other to achieve high correlation precision. The purpose of the pull-in process is to find conjugate image neighborhoods in the presence of substantial initial discrepancies. A hierarchical, or "pyramid" approach is used for the pull-in task. It is a simplified version of the Hierarchical Relaxation Correlation (HRC) method developed by HAI in the early 1980's. The HRC method uses several levels of minified images to gradually build an increasingly accurate digital terrain model, while simultaneously "relaxing" out image displacements by image shaping. At the end both images become orthorectified. The orthorectification aspect of the HRC approach leads to what may be called "correlation in object space". To accomplish this, the concept of "groundel" (ground element) was introduced. The groundels are approximately the size of image pixels projected to ground, and have x,y, and z coordinates, as well as (hypothetical) intrinsic density values. The x and y coordinates are pre-specified; the z coordinates and density values are initially unknown, but become determined better and better as the correlation progresses. This "correlation in object space" approach has been developed, and is adhered to, on the conviction that automatic correlation (least squares or not), photo interpretation, and AI-processes should be all performed in ground space, since the origin of everything recorded on the images is intrinsically in ground space. For best results, all these processes should be integrated into a single comprehensive process of object space analysis.

In the DCCS the hierarchical approach is oriented toward increasing the range and reliability of pull-in. The pull-in range should be large enough to bridge over inaccuracies in automatic estimation of point positions, e.g. due to unknown terrain elevation. However, this requirement is not overly critical, since the operator can very easily, and rapidly, eliminate cross displacements. The reliability of pull-in is critical, however, since an undetected false pull-in is likely to ruin a measurement.

MULTI-IMAGE LEAST SQUARES CORRELATION

Least squares correlation is one of the most interesting and significant concepts brought to bear on photogrammetric problems in recent years.* On the one hand, it provides a generalized approach to the correlation problem by offering a mathematically-tractable way of using multiple input data sets and solving for multiple parameters. On the other hand, it gives an access to details of correlation process, because each pixel in the correlation window can be handled individually. This offers unprecedented visibility of operations as well as flexibility in the design of solutions.

In addition, least squares correlation converts the correlation process to an adjustment problem to which photogrammetrists can apply familiar mathematical and statistical principles.

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* Because of the importance of the least squares correlation concept, an anecdote on its development may be of interest. This author became first aware of least squares correlation in 1976 through a private communication from Dr. Urho Rauhala. A program was written at Bendix Research Laboratories and tested on some limited samples of digital epipolar data available at that time. The author rated it useless, because it seemed to work in subpixel domain only. Our problem at that time was not to get subpixel precision, but to get somewhere near a few pixels! That judgement has since changed drastically.

Principles of image-to-image least squares correlation have been published by several authors [2], [3], [4], [5], [6], [7]. Concepts discussed by Grün in [4] and [5] are particularly relevant to the subject of this paper. Least squares correlation in object space, as used in the DCCS, is essentially similar to image-to-image correlation described by Grün, except that the image patches are iteratively orthorectified to (approximate) ground as the correlation progresses. In the DCCS a local ground system is established at each point. The ground topography is modelled by a simple xy polynomial, even though the available multi-image coverage might theoretically support detailed z-modelling. The density manipulations are done in ground space, instead of image space.

BLUNDER AVOIDANCE

Blunders are costly, particularly if they manage to propagate all the way through triangulation and adjustment. Obviously, blunders should be avoided if possible. The DCCS has available a range of blunder avoidance techniques. One that is conceptually trivial, but effective in practice is the automatic sequencing of point numbers. A much more sophisticated concept is that of point cluster analysis. According to it, several point candidates are measured at each tie point location, by forcing the correlator to measure several points very close to each other, yet sufficiently separated to avoid overlap of correlation windows. Because there is no overlap, the measurements are independent. In fact, experience has shown that several independent points can be found and correlated within a few square millimeters of image area. The measurements are inspected for coherence and the results are used to select the final tie point. Further sophistication, such as on-line model-by-model relative orientation and even on-line triangulation, are possible, but not available at this writing. We believe that the point cluster analysis gives sufficient protection against blunders, at a low system overhead cost.

OPERATING CONCEPTS

The DCCS is designed to make optimum use of digital automation. Two primary areas that can be optimized are the accuracy of correlation and "intelligence" of operating procedures, since the speed of correlation is so high that it is almost irrelevant in system optimization.

Given the premise that correlation accuracy is sacrosanct, optimization of operating procedures becomes of primary concern.

An almost fully automatic operation appears feasible, but not practical at this time. While the DCCS does manage to run through photographs fully automatically, it does not do so consistently. The automatic mode can be made more reliable by capturing larger image patches and using more sophisticated processing. However, the cost of required resources makes this approach impractical at this time. A semiautomatic mode, with occasional assistance and monitoring by the operator, is more economical.

Calibrations

The DCCS is very stable, requiring calibrations only infrequently. Two calibration processes are provided, one for the comparator, the other for the sensor system. The latter includes optics and electronics associated with the sensor. Once initiated, both calibrations run automatically all the way through the determination and introduction of calibration corrections. Changes in calibrations are caused primarily by variations in ambient temperature. As with all precision instruments, a stable operating environment is beneficial for optimum performance of the DCCS.

Preparations

Good preparation is essential to efficient triangulation, no matter on what equipment it is performed. The automatic planning feature of the DCCS minimizes this effort, but still requires some preparations. The operator is expected to review the photographs to familiarize himself with the structure of the block and the locations and identifications of control points, and to see if some unusual situations need to be addressed during the mensuration process. He will cause the DCCS to retrieve a pre-prepared input file, or assist him in on-line construction of such a file. The DCCS has a program module that retrieves a "skeleton" input file and permits easy modification of it in an interactive mode, either off-line or on-line. In practice, a previously used input file may be used as the skeleton to arrive at the required file content with only a few changes. The input file contains coordinates of fiducial marks, tie point locations the operator wants to use, forward and side overlaps, number of photographs per strip, etc.

Operational Flow

A specific operational flow has been adopted to optimize the performance of the DCCS under normal conditions. This, however, does not limit the universality of the system since any desired measurement can still be made manually, semiautomatically, or fully automatically. Adaptation of a preferred operational flow simply means that the normal situation is handled with high efficiency.

In terms of overall sequencing, the preferred flow results in propagation of measurements from "upper left" to "lower right", with "fly back" between strips (i.e., each strip is measured from left to right). Within each photograph the flow of measurements is as follows: Fiducial, previously captured points, new pattern points, control points, and auxiliary points (e.g. drill holes).

On the first photograph, there are no previously captured points, and some pattern points may be outside stereo coverage, while on the last photo, no new pattern points need be captured. These special situations can be handled easily using controls normally available to the operator. For example, points may be readily skipped, in both the collection and correlation phases. A recommended approach, however, is to proceed always with the normal flow. It may result in capturing and processing of a few redundant patches, but this overhead cost is a low price to pay for gaining a unified flow.

Progression of the flow is maintained by the system computer. It drives the comparator stage to locations called for by the flow, keeps track of operations to be performed during stage movement as well as at each point, maintains a default numbering system, services displays, executes automatic operations, evaluates the results, makes decisions (when allowed), updates files, informs the operator, and proceeds to the next phase, when appropriate conditions are met. Yet, the operator is always in full control. The system has provisions for step-by-step monitoring and approval by the operator. For smoothest flow and best efficiency, most flow control decisions can be delegated to the computer. It has the "good sense" to alert the operator when "something seems to be wrong".

Under normal conditions the flow has an interruption between data collection and triangulation. The purpose of the interruption is to permit a review of the mensuration results, cleaning up the files, and linking to a variety of triangulation systems. For review purposes, the system analyses the list of standard deviations resulting from least squares correlations. The RMS and maximum values of the standard deviations are displayed, with the identification number of the point at which the maximum occurs. If remeasurements are necessary, they can be done at this time. When the operator approves the measurements, the system produces an output file. The output file contains a list of point coordinates, as well as the image patches used in the final correlation. The image patches may be displayed or copied for point identification, at a later date, if desired. The coordinate list is used as an input to a linking program that makes the mensuration results compatible with the triangulation program to be used. For GIANT, the linking program is provided as a standard item. Linking programs for other triangulation systems are currently optional at extra cost.

GROWTH POTENTIAL

The Digital Comparator Correlator System discussed above has been designed to automate and streamline aerial triangulation. This is an area where digital image correlation and other digital techniques have proven capable of doing an outstanding job in terms of increasing accuracy and thruput. However, the DCCS is not a triangulator only. It is also a harbinger of a revolution to come, a foundation system capable of evolving into a comprehensive digital solution to the totality of photogrammetric data extraction problems. For triangulation, it measures a few points very accurately using certain selection principles; for generation of DTMs, it can be programmed to measure a large number of points using a different selection criteria, with models set up automatically using triangulation results.

Well-rectified orthophotographs and stereomates can then be produced digitally. Also, the way is opened for effective (semi)automatic feature extraction, with monoscopic or stereo image support. All the while, the images and the derived data remain in digital form, ready for fast access, additional processing, presentation, use, and transmission by electronic means.

CONCLUDING REMARKS

The Digital Comparator Correlator System has been described above as an automatic comparator. However, it is more than "a comparator", it represents a new departure in finding a set of comprehensive solutions to photogrammetric data extraction problems. The guiding principles of the departure stem from the realization that increased automation is an absolute necessity for significant improvements in performance of photogrammetry. The system must be primarily "automation friendly" to achieve maximum thruput and accuracy. Then, it is also optimally "user friendly" decreasing operator burden and moving the operator functions to a higher conceptual level. Implications of this philosophy to system design are far from trivial. The system described in this paper is but a starting point. Much interesting research and many efficient realizations are sure to follow. The progress will probably be rapid, because of the extraordinary vigour of digital technologies. The effect on photogrammetry will be profound.

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