DALE J. PANTON
Control Data Corporation
Minneapolis, MN 55420

A Flexible Approach to Digital Stereo Mapping*

Sophisticated matching algorithms, adaptive logic based on reliability monitoring, parallel processing, and microprogramming provide flexibility.

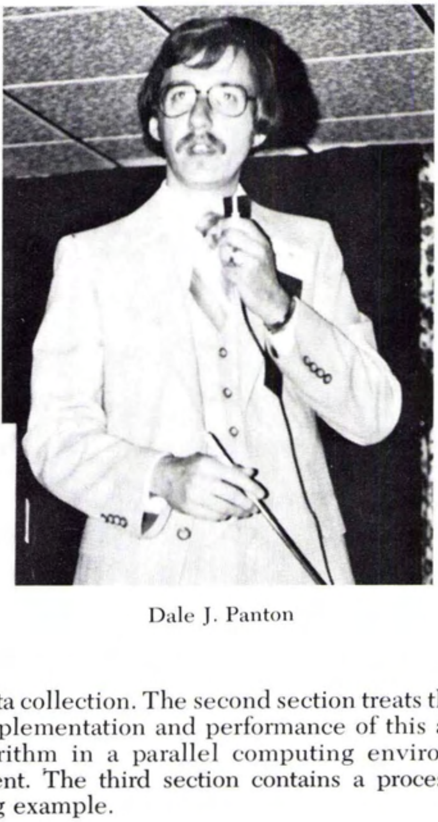
(Abstract appears on following page)

INTRODUCTION

FOR A NUMBER of years the Digital Image Systems Division of Control Data Corporation has been involved in the design and implementation of automatic, flexible, and totally digital stereo mapping systems. The work has been sponsored by the U.S. Army Engineer Topographic Laboratories and the Defense Mapping Agency. The major emphases have been the adaptive nature of mapping algorithms as they encounter different types of terrain on different types of sensor records, the practical implementation of such algorithms on extremely fast microprogrammable processors that function in parallel, and the design of an interactive digital stereo mapping and editing system.

The concept to be set forth in this paper is digital flexibility. This concept includes flexibility in algorithm design and performance, flexibility in hardware architecture, and flexibility in ultimate system usefulness. The concept addresses the problem of mapping-machine obsolescence as new requirements arise. The attempt is being made to design algorithms that can evolve by modular programming and digital hardware that can grow in modular steps rather than require redesign or retrofitting. A key means for accomplishing this is the notion of making the algorithmic portions of a mapping system as independent as possible of optical and mechanical components.

The first section of the paper covers the major functional aspects of a stereo image matching algorithm that is used for terrain data collection. The second section treats the implementation and performance of this algorithm in a parallel computing environment. The third section contains a processing example.



Dale J. Panton

STEREO MAPPING ALGORITHM HIGHLIGHTS

The basic problem to be solved in automatic digital stereo mapping is the determination of the precise geometric positions of corresponding points (features) on the focal planes of the stereo pair. Once these points have been matched up from exposure to exposure, it is a straightforward process to

---

* Presented at the ASP DTM Symposium, May 9-11, 1978, St. Louis, MO.

PHOTOGRAMMETRIC ENGINEERING AND REMOTE SENSING,
Vol. 44, No. 12, December 1978, pp. 1499-1512.

photogrammetrically intersect the corresponding rays through the points using the appropriate sensor model to produce digital terrain data in terms of X, Y, Z coordinates.

In digital stereo matching, there are essentially six coordinate systems to consider. Depending on the circumstances of the stereo exposures, some of these systems may coincide with others; but for the general case, they must all be handled independently. These coordinate systems are

- The digital scan coordinate system on the left image (denoted image A), two-dimensional;
- The photo coordinate system on image A defined by fiducial or other calibration marks, three-dimensional;
- The digital scan coordinate system on the right image (denoted image B), two-dimensional;
- The photo coordinate system on image B, three-dimensional;
- The epipolar coordinate system that relates image B to image A, two-dimensional; and
- The model coordinate system, three-dimensional.

It is desirable to define a regularly spaced grid in one of the coordinate systems to drive the matching process. The location of this grid is a factor in determining the number, complexity, speed, and accuracy of the image processing functions that are collectively called stereo matching.

BLOCK MATCHING CONCEPTUALIZATION

The basic idea behind the current matching method is to define a regularly spaced grid of points on image A, and then for each of these points to find the conjugate point on image B. The justification for this scheme can be found in Panton and Murphy (1977). The corresponding point is found by correlating a group of pixels surrounding the point on image A with a sequence of groups of pixels on image B. The groups of pixels are termed blocks or patches, and the sequence of patches on image B defines a correlation search area. These concepts are illustrated in Figure 1.

Digital scan lines are generally oriented normal to the flight direction and direction of major parallax. Processing occurs from left to right, or in the direction of increasing x coordinate on image A. A column is defined as a line of patches which lie on the same digital scan line or whose centers all have the same x coordinate on image A. The sequence of processing is to correlate all the patches of a column before moving on to the next column. This scheme allows a rather straightforward management of image A data. That is, the image A buffer window need only be wide enough to contain one correlation patch width of scan lines.

As can be seen in Figure 1, the corresponding line on image B of a single scan line on image A can be rather non-linear due to the effects of terrain relief. This corresponding line cuts across many digital scan lines on image B; thus, the image B buffer window must be considerably wider than the

ABSTRACT: *A flexible algorithm has been developed to meet the changing requirements for generating terrain data from digital stereo sensor records. The algorithm includes an image matching procedure in which parallax components are determined by automatically correlating corresponding image features. The algorithm is adaptive and can handle various types of sensor and natural terrain conditions. Reliability monitoring of the output terrain data is performed on the basis of the in-process analysis of local image areas. The reliability measure dictates various strategies that the algorithm can apply in image areas where automatic correlation is difficult.*

The algorithm was implemented on a distributive network of parallel digital processors. In this system, production speed is attained because of the inherent parallelism of the modular processors. Flexibility is maintained because the processors are microprogrammable. In this way, new sensor imaging characteristics and new algorithm strategies can be incorporated without disturbing the fundamental software and hardware structure of the system. Production times for compiling a representative stereo model on this parallel configuration far exceed the capability of general-purpose computers.

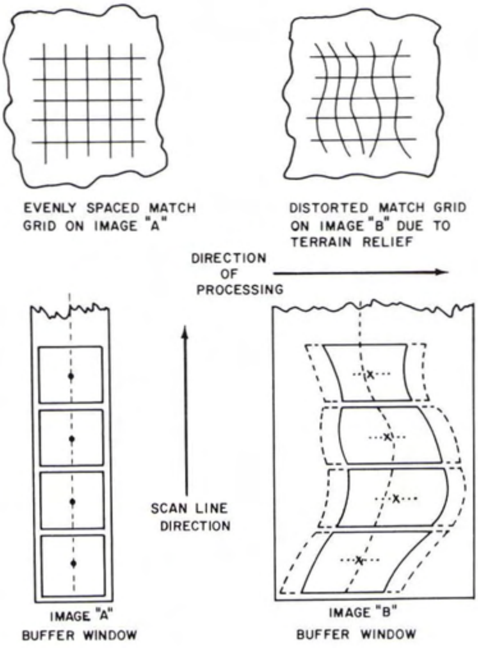


FIG. 1. Block matching conceptualization.

image A buffer window. In addition, the size, shape, and orientation of the corresponding patches on image B can be quite different from the nominally rectangular patches on image A, also due to terrain relief and the geometry of the stereo exposures.

The conceptual steps in finding a match point are as follows:

- Determine the next point to be matched along the evenly spaced grid of image A;
- Using epipolar geometry, compute the equation of the epipolar line passing through the point to be matched on image A;
- Compute the equation of the corresponding epipolar line on image B;
- Predict the location of the corresponding match point position on image B along the epipolar line using neighboring, previously matched points;
- Define correlation sites on each side of the predicted location on the epipolar line;
- Shape the image B patch and search area using previous and predicted match point information so that the image B patch most closely lies on the terrain and most closely conforms to the information content of the image A patch;
- Compute a correlation coefficient for the predicted match point location and for each search site;
- Determine the site of maximum correlation and fit a smooth quadratic function through it and its two neighbor sites to determine the correlation function maximum to a fraction of a pixel;
- Compute the reliability factor of the match point based on a set of reliability criteria;
- Apply a correction to the match point if it is excessively unreliable; and
- Update the correlation history data and prediction mechanism based on this new match point and reliability.

The primary output of the matching algorithm is a file of five-tuples, one corresponding to each match point found. This five-tuple is illustrated in Figure 2 along with the basic terminology of the algorithm. x and y are the digital scan coordinates of an evenly spaced grid point on image A. u and v are the digital scan coordinates of the corresponding point on image B; v is actually computed in the epipolar line determination, u is found by the correlation search along the epipolar line. R is the computed reliability factor of the match point.

Detailed descriptions of the algorithm functional components are not within the scope of this paper. These can be found in Panton and Murphy (1977). However, the major algorithm emphases will be discussed in the following sections.

ALGORITHM TUNING

The basic philosophy behind the block matching system design is that the ideal situation for matching the images of a stereo pair is to match each pixel of one image individually with its corresponding position on the other image. However, as long as the correlation coefficient is used as the similarity metric between the images, matching one pixel with one pixel is not possible because of the low statistical significance of such a small sample. Therefore, it is necessary to

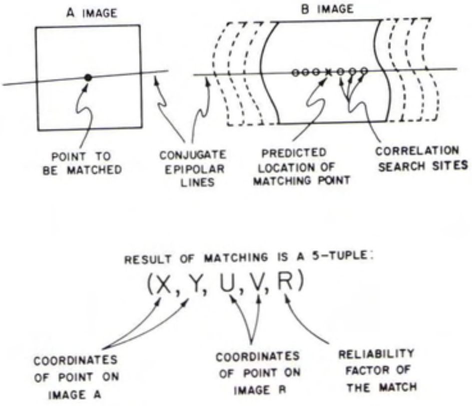


FIG. 2. Block matching detail.

measure the similarity of a group of pixels surrounding the pixel in question. The size and shape of this group, or image patch, must be chosen carefully and may vary from image to image and also from area to area in the same image. The underlying objective is to choose as small a patch as possible such that the local image noise and lack of feature content do not dominate the value of the correlation coefficient for that patch. To this end, the way the algorithm perceives imagery and terrain can be changed by altering a set of control parameters that are referred to as tuning parameters. The motivation behind this design is that the algorithm must behave differently for different image and terrain events that can occur. The nature of these different events is determined by the type of sensor used, the stereo taking conditions, and the highly variable characteristics of the terrain that is imaged.

Tuning parameters can be made to dynamically vary during the course of matching and can be entered and altered by a human operator. Some of the more important tuning parameters are as follows:

- Image A match point grid limits and interval sizes; a grid cell need not be square as indicated in Figure 1;
- Correlation patch size in two dimensions; again, the patch need not be square as in Figure 1;
- Number of correlation sites along the search segment;
- Prediction function weighting coefficients; and
- Reliability thresholds for the correlation coefficient, standard deviation, prediction function range, and slope of the correlation function.

An experiment was conducted on a particular set of imagery to understand the effects of tuning changes. Fifty matching runs were made on the same area of imagery that contained approximately 1,000 match points. The tuning parameters were varied one by one from one run to the next in an effort to constantly increase the matching reliability. The result was that the matching reliability for all the tuning cases ranged from a minimum of 49 percent to a maximum of 82 percent. Each tuning case changed the behavior of the algorithm to certain types of terrain. It was observed that small changes to the values of the tuning parameters sometimes made very large changes in algorithm behavior. The best matching seemed to occur when the process was tuned such that it was on the brink of instability. In this way, the algorithm was most responsive to terrain variation, yet stable enough to track the image accurately from one end to the other.

PREDICTION MECHANISM

When matching images, heavy reliance on values of the correlation coefficient alone is a rather unreliable approach in terms of the accuracy of any given match point. Driven solely by correlation maximum searching over extended areas, patches and match points can wander considerably from their true positions depending on the geometric distribution of image noise and high frequency signal components. Therefore, it is necessary to apply a great deal of geometric constraint to correlation patches and match points based on known geometric parameters and the continuity and slope limits of natural terrain.

Epipolar geometry provides the primary constraint on the stereo matching process. The underlying concept is that corresponding points of the stereo pair must be on corresponding epipolar lines except when there is excessive film distortion or air refraction. Thus, in forming a match point on image B, the v coordinate discussed previously is derived strictly from the relative geometry of the exposures, eliminating the need for a correlation search in a direction normal to the epipolar line.

However, a prediction is necessary for u, the parallax coordinate on image B. This u prediction must primarily take into account the local terrain relief displacement on the images in the area to be correlated. The basic idea is to make this prediction accurate enough so that correlation only has to be performed for one or two pixel sites on either side of the predicted location. The ideal running situation in automatic matching occurs when the tuning parameters are set correctly for the imagery, the image quality and feature content are high, and correlation maxima are found within one pixel of their predicted locations.

Predictions are made along the short line segments that join match points by the use of local velocity or rate of change functions. This concept is illustrated in Figure 3. In the present matching algorithm, the evenly spaced grid to be matched is defined on image A. Therefore, the distance between grid lines of constant x is constant across the image and is termed Δx. The corresponding distances, Δu, on image B are variable and depend on the exposure station positions and orientation and on the slope of the imaged terrain. As can be seen in the figure, the rate of change of image feature placement,

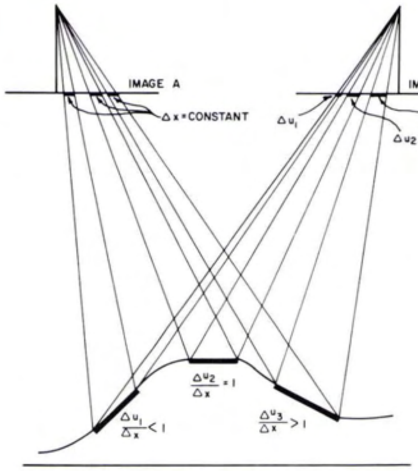


FIG. 3. Differential rate of change function, $\Delta u/\Delta x$.

$\Delta u/\Delta x$, is one in all cases for flat terrain. Then $\Delta u/\Delta x$ is less than one or greater than one depending on whether the terrain slopes toward or away from exposure station A over the small line segment. By utilizing these small linear differentials, a high order modeling of the terrain surface is achieved in simple computational steps.

Analytically, the relationship between the velocity function $\Delta u/\Delta x$ and the actual terrain slope $\Delta h/\Delta X$ is:

$$\frac{\Delta u}{\Delta x} = 1 - \frac{B \dfrac{\Delta h}{\Delta X}}{H + X_1 \dfrac{\Delta h}{\Delta X}}$$

or inversely,

$$\frac{\Delta h}{\Delta X} = \frac{H\,(1 - \dfrac{\Delta u}{\Delta x})}{B - X_1\,(1 - \dfrac{\Delta u}{\Delta x})}$$

where B is the baseline distance between exposure stations, H is the altitude of the exposure stations above some reference datum, and X_1 is the model distance of a point of interest from the nadir of exposure A relative to the baseline distance. These relationships are for the ideal case of vertical photography; the effects of platform tilt are not considered. The equations have been included in this form for simplicity of illustration.

CORRELATION PATCH SHAPING

The correlation and consequent match point determination of an individual patch is not independent of neighboring patches and match points. Moreover, the correlation of image areas introduces a certain averaging effect on the actual point that is matched, the effect increasing as the size of the areas increases. Therefore, it is necessary to shape the image data within a correlation patch so that it conforms to all the match points in the vicinity. In this way, the averaging effect is confined to small linear segments between the match points. Previous matching studies have shown that correlation patches that are the same size and shape on both images of the stereo pair are by no means adequate for performing terrain mapping. The only case in which similar patches apply is the case of flat, non-varying terrain. A quantitative justification for this can be found in Panton and Murphy (1975a).

Referring to Figure 4, depending on the selected patch size on image A with respect to the selected matching grid intervals (Δx and Δy) there can be any number of "subpatches" defined by the grid within the total patch area. On image B, these subpatches can all be of different shapes in highly varying terrain. Therefore, the patch shaping algorithm has been designed to use the $\Delta u/\Delta x$ values on the sides of the subpatches as shaping factors for each individual subpatch. For example, if the subpatch side (or Δx on image A) is ten pixels, and if the $\Delta u/\Delta x$ value for that interval is 0.6, then the corresponding subpatch side on image B is six pixels. For pixels lying within a subpatch, the shaping factors are linearly interpolated from the well-defined subpatch side values. The result is that the terrain surface within a patch is being modeled in terms of planar facets such that the patch conforms to the terrain as closely as possible, and the shaped image B patch resembles the image A patch in feature content as closely as possible.

In the implementation of the shaping scheme, digital image resampling plays an integral part. The shaping algorithm must extract from the image B buffer data the correct number of gray scale samples for correlation with the image A patch. These samples do not necessarily lie at pixel centers on the image B digital raster. Using the example above, to correlate a ten pixel wide subpatch that covers only six pixels on image B, ten gray scale values must be resampled from the six. A bi-linear resampling scheme has proven to be more effective here than a nearest-neighbor approximation.

RELIABILITY MONITORING

In an effort to provide algorithm self-

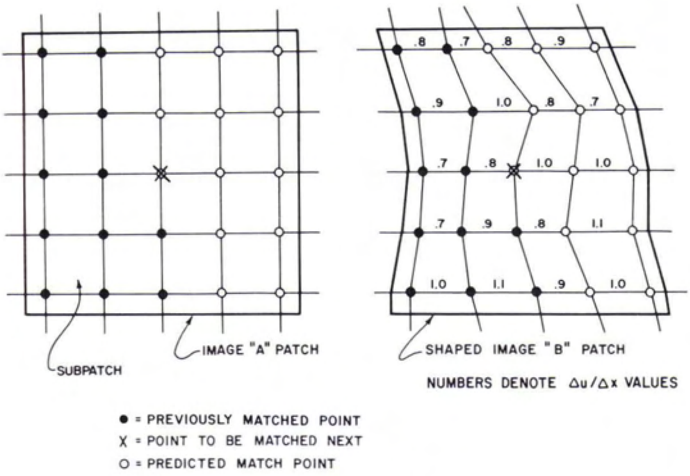


FIG. 4. Correlation patch shaping.

determination and to allow for match point corrections, a reliability factor has been designed into the algorithm. In this way both the algorithm itself and the analyst running the algorithm can have an indication of how the matching is progressing. Referring to Figure 5, a number of reliability criteria have been set up such that the N digit reliability factor contains one digit for each criterion. In the current algorithm design, there are five criteria, as indicated in the figure; but this number can be increased as more or different process characterization functions come into use. There is also a hierarchy among the criteria such that the most important occupy the most significant digits of the reliability factor. A reliability factor is generated for each point matched, and if a point is reliable with respect to all the criteria, its factor is zero. However, if a match point determination fails one of the criteria, the corresponding digit in the reliability factor becomes nonzero.

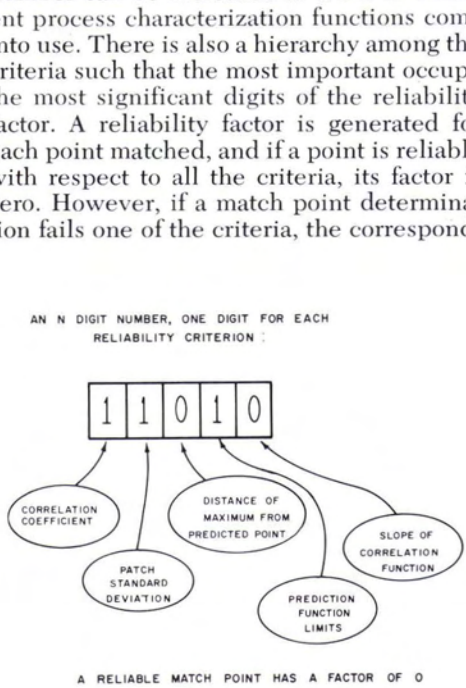


FIG. 5. Reliability factor.

The reliability factor essentially serves three main purposes. Internally, it functions as a decision table for the algorithm to trigger various match point correction strategies. Externally, it functions as an analysis tool to aid the user in the selection of algorithm tuning parameters and in the development of further algorithm refinements. And finally, it serves as a weighting factor for all subsequent processes that utilize the match points or digital terrain data. Consideration of the first function opens up an entire area in need of further development. Analyses must be performed relating to specific problem area symptoms so that the algorithm may be "trained" to handle more complex image and terrain events. The difficult aspect here is not so much the design and implementation of the strategies themselves, but rather the design of the detection algorithms that dictate when a specific strategy is to be applied.

MATCHING ALGORITHM IMPLEMENTATION IN HARDWARE

General-purpose computers, as a rule, are impractical for implementing large volume image processing applications. For example, a large scientific computer such as the CDC 6400 would expend 20 hours to generate digital terrain data for a typical model area using the above described algorithm. To achieve the rates of a production environment, what is practical is the incorporation of the desired algorithm in a hardwired machine that is capable of the utmost parallelism and processing speed. However, this method of implementation is rather inflexible as regards algorithm modification, evolution, and machine versatility.

An alternative is to implement a collection of extremely fast modular processors that can function cooperatively, in parallel for a particular application. The speed of such processors can approach that of hardwired machines, and algorithm flexibility is maintained in that the processors are microprogrammable. In addition, system flexibility is inherent in this approach because a system can grow and increase in performance by the addition of more processors. This concept of modular hardware also extends to bulk memory modules, peripheral controllers, and display interfaces.

PROCESSOR ARCHITECTURE

CDC has developed such a set of hardware building blocks specifically for digital image processing applications. The modular processor is called the Flexible Processor (FP). Its characteristics are listed in Table 1. In itself the processor is a full, high performance computer, organized with a dual bus architecture. Its internal organization is illustrated in Figure 6. The processor is capable of performing eight million instructions per second. The register files shown in the figure are 60 nanosecond semiconductor memories that have simultaneous read/write capability.

TABLE 1. CDC FLEXIBLE PROCESSOR CHARACTERISTICS

- Microprogrammable-Random Access Microcontrol Memory
- 32-Bit or 16-Bit Word Lengths
- Array Hardware Multiplier
- 16-Level Hardware Priority Interrupt Mechanism—Three-Level Mask Capability
- Specialized Logic for Square Root and Divide
- 8 MHz File Buffered Word Transfer Rate—16-Word by 32-Bit or 16-Bit Input File Buffer
- 2 MHz Direct Memory Access Word Transfer Rate
- 1 MHz Register-Buffered Word Transfer Rates
- Dual 16-Bit Internal Data Bus System
- 0.125 μs Clock Cycle
- 0.125 μs 32-Bit Addition: 0.250 μs Byte Multiplication
- Register File Capacity Up to 4128 16-Bit Words
- Hardware Network for Conditional Microinstruction Execution—Four Mask Registers and a Condition Hold Register

These standardized Flexible Processors can be cabled together in configurations, with the inclusion of bulk memory modules, to provide a very powerful computing resource. There are three basic types of communication channels that can be used to connect processors. The A/Q channel is a slow, one megahertz channel used primarily for single word transfers of control information from processor to processor. The DSA channel is a two megahertz data channel that is used for accessing data from an external MOS bulk memory. The third type of channel is the high-speed channel used for interprocessor data communication. The transfer rate on this channel is eight megahertz (16 megapixels per second), making it ideal for transferring image data from processor to processor.

LEVELS OF PARALLELISM

The approach used to implement an algorithm on a configuration of these types of processors is one of distributive computing. In this approach an algorithm is divided into its basic functional modules. These modules are then distributed among the available processors such that each processor performs its given section of the algorithm simultaneously with the other processors and sections. This approach to parallelism differs from the parallelism arising from array processing. In array processing, all processors in the configuration are loaded with the same instruction or function, and upon command, simultaneously perform that function on contiguous elements of data.

Three levels of parallelism are present when implementing algorithms on distributive systems such as Flexible Processor configurations. These are the instruction logic level, the processor level, and the systems level. On the instruction logic level, parallelism arises from the fact that more than one operation can be performed in a single microinstruction. The Flexible Processor is organized such that there are two separate data buses that connect two input files, two temporary files, two large files, and two adders. Therefore, 16-bit operands may be routed among these components independently and in parallel over either bus. For example, a 16-bit number in a temporary file location may be sent to the adder over one bus; while, at the same time, two 8-bit pixels may be transferred from an input file location to a large file location on the other bus; while, at the same time, the hardware jump stack may be incremented or decremented. All of this occurs in one instruction cycle, the sequence

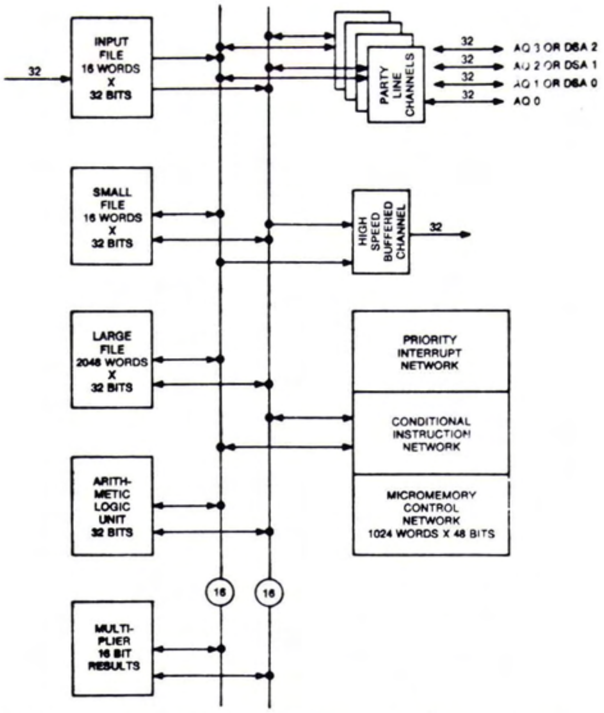


FIG. 6. Internal organization of the CDC Flexible Processor.

of events being synchronous with the internal timing scheme of the instruction. Some of this parallelism is lost, however, when 32-bit operands are processed because both buses are required. To implement a fast algorithm, it is of the utmost importance to sequence the individual operations of the algorithm in such a way that the maximum parallelism is achieved at the instruction level. A truly optimized algorithm is one in which both buses are kept busy through most of the instruction cycles.

On the processor level of parallelism, the main concern is how much parallelism can be achieved among the processors of a given configuration. It is on this level that distribution of algorithm modules over the processors is important. The major objective is to distribute the modules such that no processor is left idle an excessive amount of time during the execution of the algorithm. Flexibility is attained on this level if the processors are implemented in an asynchronous fashion. Thus, each processor in the configuration functions as an independent unit; when it finishes its task, it waits on a flag or interrupt for more data to perform its task again. However, there is more communication overhead in this asynchronous approach than in an approach where all processors operate in synchronism. The benefit is modularity; one processor's task may be altered without significantly affecting the timing of the other processors.

The third level of parallelism, the systems level, exists if Flexible Processors are configured into separate, but duplicate, processing channels. Here, the microprograms are the same for each channel but the algorithm is run in parallel over different sections of digital image data. For example, if there are four processing channels available, then the imagery can be partitioned into four adjacent sections such that one channel processes one section simultaneously with the other channels and sections. Theoretically, then, a four channel system can realize a fourfold increase in total throughput rate over a one channel system. However, additional overhead is incurred if it is necessary to link the parallel channels together with parametric data.

System expandability is possible on both the processor level and systems level. If the algorithm is expanded or if increased performance is desired, additional processors may be included within a channel or additional channels may be incorporated in the system.

BENCHMARK TEST

The stereo matching algorithm was implemented on the hardware architecture described above as a benchmark test to establish the credibility and production speed of the algorithm design and the distributive processing concept. The actual benchmark system is shown schematically in Figure 7. This system is experimental in nature and was configured to facilitate interactive image analysis and research. The primary computational units of the system are the CDC 1700 computer and a configuration of four Flexible Processors. The remaining boxes in the diagram are peripheral units. The boxes labelled SMD are storage module drives. These are high performance disks that are accessible by Flexible Processors through a data channel controller.

The CDC 1700 is a standard minicomputer that is used as a host computer to communicate with the outside world. This host computer runs an operating system that controls the peripherals, maintains a file system, interacts with an operator, and manages data coming to and from the Flexible Processors. The actual matching algorithm is distributed over the four Flexible Processors. The basic sequence of operations is as follows: the host computer loads the parallel processors with their respective microcode modules, relays parameters entered by an operator to the parallel processors, and then transfers system control to the parallel processors. At this point the host computer goes into an idle loop and is used by the parallel processors as another low-speed peripheral device on an interrupt basis. Within the parallel configuration, one of the processors is programmed as an executive to control and synchronize the data flow in the system. System control is retained by the executive processor until the processing terminates or until the operator interrupts the system for interaction. The details of algorithm distribution and operational flow in the benchmark can be found in Panton and Murphy (1976).

A summary of the benchmark performance is given in Table 2. This represents an average tuning case. The algorithm can actually run faster or slower depending on the grid interval size, patch size, and number of correlations performed per point. The timing aspects can also change dramatically by distributing the algorithm over more processors and by adding additional processing channels. Four processors in a one channel configuration were used for the benchmark be-

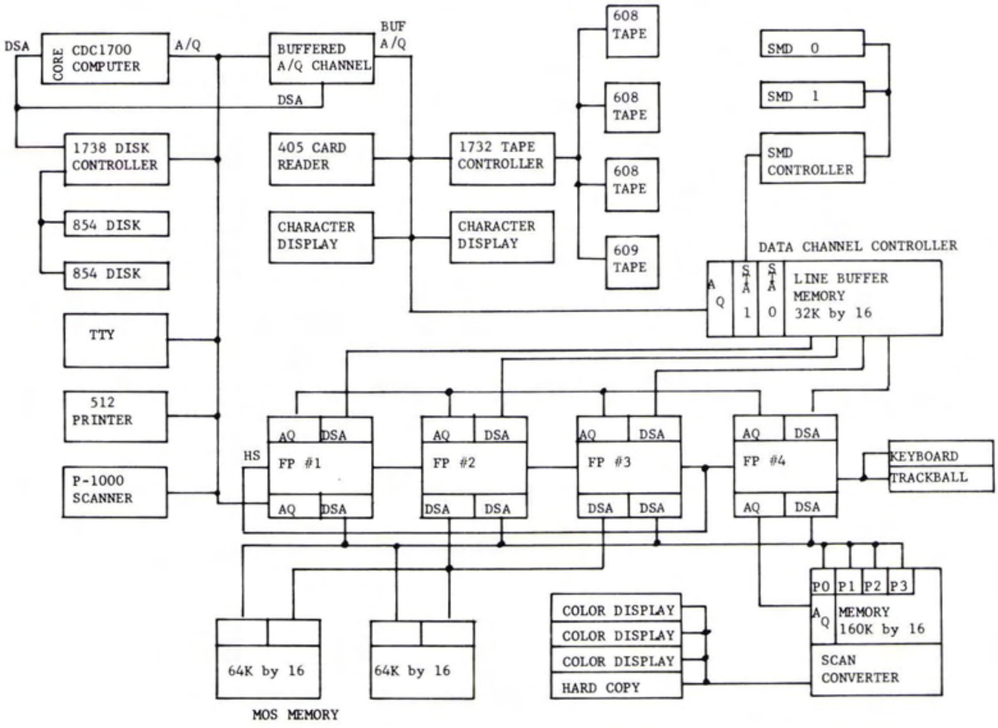


FIG. 7. Benchmark hardware configuration.

cause the test was performed on an existing, experimental system.

TABLE 2. BENCHMARK PERFORMANCE SUMMARY FOR A REPRESENTATIVE CASE

Patch size	21 by 21 pixels
Matching grid interval	8 by 10 pixels
Correlation search size	5 sites
Image size	5000 by 9000 pixels
Match points per model	562,500
Benchmark time per match point	0.0037 seconds
Benchmark time per model	35 minutes
CDC 6400 time per model	20 hours
Speed increase of benchmark over CDC 6400	34 times
CDC 6600 time per model	11 hours
Speed increase of benchmark over CDC 6600	19 times
Benchmark throughput rates	270 match points/second 119,000 pixels/second
Equivalent add operations per patch	29,600
Equivalent add operations per pixel	67

PROCESSING EXAMPLE

To illustrate the behavior of the stereo matching algorithm described in this paper, a stereo pair taken over the Phoenix-South Mountain area in Arizona was processed. The scale of the photography is 1:48 000, the focal length of the mapping camera being nominally six inches. Two-by-two inch sections from the original photos were digitized at the U.S. Army Engineer Topographic Laboratories (USAETL) using a 35 micrometre scanning spot size over a 24 micrometre interval. This resulted in two digital images that are 2,048 by 2,048 pixels. A pixel side corresponds roughly to four feet on the ground, but a mismatch or parallax error of one pixel results in about 7.7 feet of vertical error on the ground. The mensuration and interior orientation of the photos were also performed at ETL.

Figure 8 is denoted image A of the stereo pair. The size of this digital image is approximately 1,260 pixels by 2,032 scan lines. It is considerably enlarged for illustrative purposes and has been digitally enhanced since the gray-scale range of the original digital data was rather narrow. The black lines on the picture are the evenly spaced matching grid lines in the parallax direction. These lines are spaced eight scan lines apart. Along

FIG. 8. Image A with evenly spaced grid superimposed.

these lines matching occurred at every tenth pixel, so for this image section, 53,910 match points were generated. A majority of these points were matched using a 21 by 21 pixel correlation patch over a seven-site search segment.

Figure 9 shows the conjugate grid superimposed on image B. This grid plot was produced by plotting straight lines between all the match points lying in the same column. The plot, then, is actually a picture of the match points and also of the parallax function that relates image B to image A. If Figure 8 and Figure 9 were viewed under a stereoscope, the corresponding lines would fuse stereoscopically and the grid would appear to lie on the terrain in three-dimensional space.

The match points were photogrammetrically intersected using the absolute orientation elements to produce a file of digital terrain data. The elevations were then contoured at 20-foot intervals. The resulting digital contour image superimposed on image A appears in Figure 10. Neither the terrain data nor the contour lines here have been smoothed. The contouring procedure makes use of local surfaces defined by bicubic polynomials that fit the data exactly; least squares techniques are not used. Since this contour image is generated in image A space, it is unrectified with respect to model or object space. However, the contour labels on the edges do represent actual feet above sea level on the ground.

A portion of the same digital terrain data was used to generate the three-dimensional perspective plot of Figure 11. The vertical dimension of the data has been exaggerated with respect to the horizontal for analytical purposes. No fitting or smoothing of the data was performed for this plot; the actual model coordinates of match points were simply connected by straight line segments.

Figure 12 is a plot of the reliability factor for each match point superimposed on a lightened version of image A. The more unreliable a match point is with respect to the five reliability criteria, the darker is its grayscale value in this picture. For this processing example, of the 53,910 match points processed, 72 percent are reliable. Most of the unreliable areas observed in the picture are due to a low standard deviation of the image intensity in those areas. In these pictures, north is to the left. A large number of unreliable areas consistently fall on the north slopes of the mountain ranges. These slopes are highly illuminated and notably lacking in feature content. A specific example is the circular area at the top edge of the picture. Looking back at Figure 8, it is evident that this unreliable area lies on a steeply sloping, conical peak whose entire northern exposure is rather featureless. Matching was very difficult in this area, and

FIG. 9. Image B with corresponding grid superimposed.

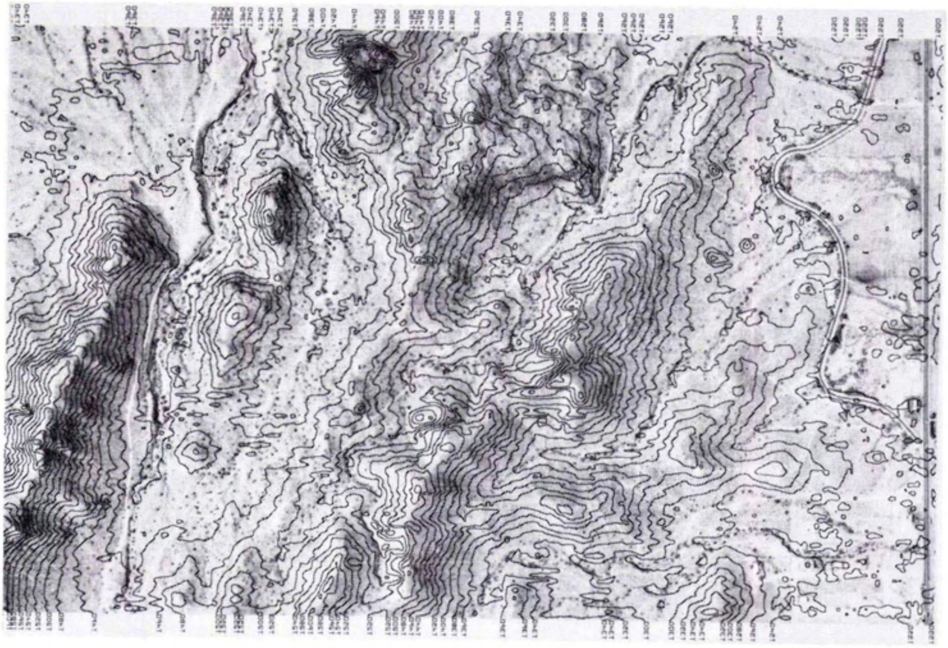


FIG. 10. Image A with digital contours superimposed.

the mismatching is manifested in the false contouring of this peak in Figure 10. However, the matching process did not break down completely after encountering this area. The match point reliability increased as the feature content improved on the other side of the peak. Other unreliable areas were not as dramatically inaccurate; in fact, some—though flagged as unreliable—were remarkably accurate.

CONCLUSION

Throughout its continued development, the matching algorithm has become somewhat of a terrain and sensor analysis tool rather than a strict stereo compilation technique. Under the tuning parameter concept, it is possible to apply the algorithm to a wide range of sensor, image, and terrain conditions. Using the algorithm's built-in reliability analysis, it is possible to assess the difficulty and quality of automatic matching under these varied conditions. It has been found that no single digital technique can approximate the capability of a human stereo compiler when faced with varied sensor records and diverse image and terrain events contained in these records. This is the jus-

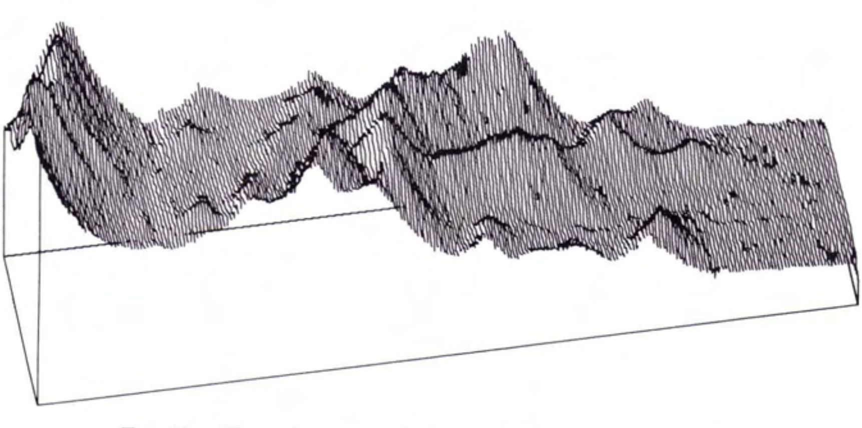


FIG. 11. Three-dimensional plot of block process terrain data.

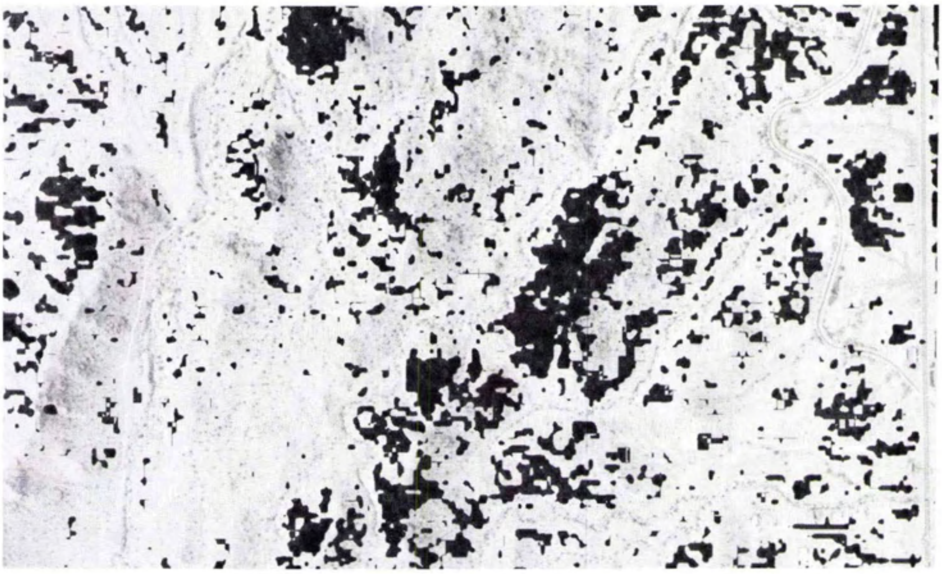


FIG. 12. Image A with reliability plot superimposed.

tification for algorithm tuning. Moreover, the stereo conditions that are optimal for human compilation are not necessarily optimal for automatic matching and vice versa. This is the rationale behind reliability monitoring. The overall objective is to exercise the algorithm under representative experimental conditions so that decisions can be made and parameters acquired regarding what actually is optimum for automatic stereo mapping.

Future development, then, will concentrate on the design of digital strategies that can collectively provide a stereo mapping algorithm with more intelligence in perceiving varied image and terrain events. Even though the primary output of such algorithm is digital terrain data, there is a great deal of parametric information about the terrain geometry and composition that can be derived in the same pass over the imagery. When collected, this information can be picked up in file form by subsequent processes which perform texture analysis, feature extraction, planimetric line following, or statistical determinations. The trend then will be toward the development of digital data base structures in which original imagery and terrain will be characterized symbolically, rather than in continuous tone or gray-shade form. Future problems to be solved will center around the creation, updating, and matching of these symbolic data base structures.

In the hardware domain, the costs of processors and memories are decreasing, while at the same time their speed and size are increasing. Already modular processors are being designed that can realize a tenfold increase in speed over the Flexible Processor described above. With more computational power and larger memories, mapping algorithms can become more sophisticated and still meet production requirements.

A highly probable scenario for the future, then, includes large integrated mapping systems that service extensive digital data bases. These systems will include many parallel channels that can be made to be multifunctional by loading into them the appropriate applications modules. The functional mix among the channels will be monitored and controlled by collections of independent, interactive work stations. These stations will serve as "windows" into the data base and the processing environment. For example, in one channel a user may be generating digital terrain data as part of a production cycle while in another channel a second user is producing digital orthophotos and contour manuscripts from the previous day's terrain data. In still another channel a third user may be performing feature extraction for a planimetric or simulation data base while a researcher on a fourth channel is experimenting with a new matching strategy or developing a new sensor triangulation model. This idealistic scenario can be carried on indefinitely. But the point to be made is that diverse data from many sources can, within the same system, be produced, catalogued, linked up, and retrieved for a wide variety of mapping applications.

REFERENCES

Panton, D. J., and M. E. Murphy. 1975a. *Digital Cartographic Study and Benchmark: First Interim Technical Report,* U.S. Army Engineer Topographic Laboratories, Fort Belvoir, Virginia, October 1975.

_________. 1975b. *Digital Cartographic Study and Benchmark: Second Interim Technical Report,* USAETL, Fort Belvoir, Virginia, December 1975.

_________. 1976. *Digital Cartographic Study and Benchmark: Third Interim Technical Report,* USAETL, Fort Belvoir, Virginia, September 1976.

_________. 1977. *Digital Cartographic Study and Benchmark: Fourth Interim Technical Report,* USAETL, Fort Belvoir, Virginia, July 1977.

CALL FOR PAPERS

Seventh Biennial Workshop on Color Aerial Photography in the Plant Sciences

May 15-17, 1979
Faculty Club, University of California
Davis, California

The Workshop will feature vegetation damage assessment, land use planning, vegetation mapping, and related fields of agriculture and resource management. If you are engaged in any discipline related to vegetation, from Agronomy to Zoology, this workshop should be of interest. As in previous years, the focus will be on the latest information on use and misuse of color and color infrared photography. An informal poster session with emphasis on techniques, tools or displays will be part of this workshop.

If you would like to present a paper at this workshop or participate in the poster session, we ask that you supply the following information:

- Title of Proposed Paper
- Author's Name, Address, Position, and Professional Affiliation
- Summary of Technical Content of Paper, approximately 200 words. (Note: this is not an abstract and will be used for review purposes only)
- Estimated Time of Presentation (not to exceed 20 minutes)
- Visual Aids Required

In order for papers to be considered for inclusion in the program, proposals must be received no later than March 15, 1979. Please submit proposals to

Planning Committee
Workshop on Color Aerial Photography
Attention: Mr. William M. Ciesla
USDA Forest Service
FI&DM/Methods Application Group
2810 Chiles Road
Davis, California 95616