186, 240-248 (1979)

Automatic stereo reconstruction of man-made targets*

Robert L. Henderson, Walter J. Miller, C. B. Grosch
Information Sciences Division, Control Data Corporation
Minneapolis, Minnesota 55440

Abstract

This paper reports development of an automatic procedure for measuring and representing three-dimensional geometry of man-made sites from stereo reconnaissance photography. The ability to derive such information from remotely sensed data has application within both the military and intelligence communities. Studies of typical reconnaissance have shown that precise models can be extracted, but current methods are laborious, and rely heavily on operator insight. This work addresses development of an automatic and digital method. Attention is restricted to sites composed of planar surfaces (e.g. buildings). For an automatic stereo system, these sites present the severe problems of abrupt change in slopes and image occlusion. These features thoroughly disrupt application of traditional automatic stereo techniques, which have been developed to model rolling natural terrain. The system reported here represents an entirely new design, based on correlation but specifically structured to the problem features of planar surface sites. A demonstration is achieved, on reconnaissance imagery, of automatic stereo measurement of a building complex. This work is expected to form a basis for advanced work in both automated and computer aided stereo technique.

Introduction

This paper reports an automatic procedure for measuring and representing three-dimensional geometry of man-made sites from stereo reconnaissance photographs. The ability to recover such information from remotely sensed data has wide military and intelligence application. The particular application motivating this work is development of a highly precise terminal phase guidance system for the cruise missile. In this application, accurate knowledge of target three-dimensional geometry provides a basis for development of a target area map, or "reference", in support of real time correlation guidance.

The principles of construction of three-dimensional models from reconnaissance photography are well understood, and have been in application for many years in the stereo mapping community. The process uses two or more views, each taken from a different camera station, of the area to be mapped. Any given point in the target area can be located by identifying coordinates of images of that point in two or more views. The resulting "match-point" coordinates, coupled with information on the imaging geometry, allow the target point to be located by intersection of rays in 3-space.

The central problem is that the number of "match-points" required for construction of a single detailed model can be of order 10^6. It is therefore desirable to automate the process insofar as possible. The work reported here concerns development of a digital approach.

Automated stereo mapping is not new (1). What is new in this work is the application to man-made, cultural targets. This is in fact an overriding requirement. Automated stereo systems, existing at the outset of this work, have all been designed for application to rolling natural terrain. Over cultural areas, these systems break down, for reasons which go to the heart of the system design assumptions. Therefore, new technology is required, and the goal of this work is simply to demonstrate the feasibility of the required automated measurement.

The strategy for this demonstration has been to divide the problem according to the geometric complexity of cultural sites. The initial effort, reported here, is restricted to sites composed of planes (e.g. buildings). Development of techniques for more complex surfaces is a subject for further work. Nevertheless, the planar surface sites include many targets of interest, and introduce complexities beyond the scope of terrain mapping systems.

This paper reports a demonstration of feasibility of automated stereo measurement over planar surface sites, and describes key concepts of the algorithms by which this demonstration was achieved.

Problem Specification

The problem is as follows. Given two views of a target complex composed of planes, identify the target geometry through measurement of corresponding points on these views. For instance, a simple procedure might be to number the target vertices, and then, for each vertex, identify its coordinates on each of the input views. From this information, the location of each vertex is three-space can be inferred and a target model subsequently constructed.

The goal of this work is to perform this operation as automatically as possible. It is first necessary to

* Developed under sponsorship of USAF Rome Air Development Center, Griffiss AFB, N.Y. 13441, Contract No. F30602-79-C-0081.

select a general approach. The vertex-numbering method described above, although conceptually simple, is extremely difficult to implement in an automatic mode. An enormous amount of experience and intelligence is involved in organization of the target into vertices, given only photographs of the target, and in development of the corresponding organization of the views.

For implementation on a digital computer, the process is conveniently approached through image correlation techniques. In effect, matching points are identified by location on different input views of regions exhibiting similar intensity variation. Such an approach is amenable to analytical (hence numerical) study. Its successes and failures will define portions of the problem where more ad hoc methods (e.g. edge matching) must be tried.

Such "gray scale matching" is the basis of current automated techniques for stereo processing over natural terrain. A critical assumption in such systems is that the relief distortion between input images, which is to be measured, is continuous and smoothly varying. Exploiting this assumption, these systems first acquire matching in some small region of the imagery, perhaps with operator help. Then, small areas to be correlated are advanced incrementally away from this region to "track" distortion across the images.

For image matching over cultural targets, the assumptions underlying this design are violated in fundamental ways. Image distortions change abruptly to correspond to sharp changes in target slope (e.g. at building corners). The distortion exhibits outright discontinuities, called occlusions, where a portion of the target is hidden in one image, and visible in the other. Further, these problems are most severe at points of greatest interest, namely building vertices. To illustrate, Figure 1 shows the distortion of a small area, such as might be employed by a terrain mapping system, which has been matched between two images in the neighborhood of a building vertex.

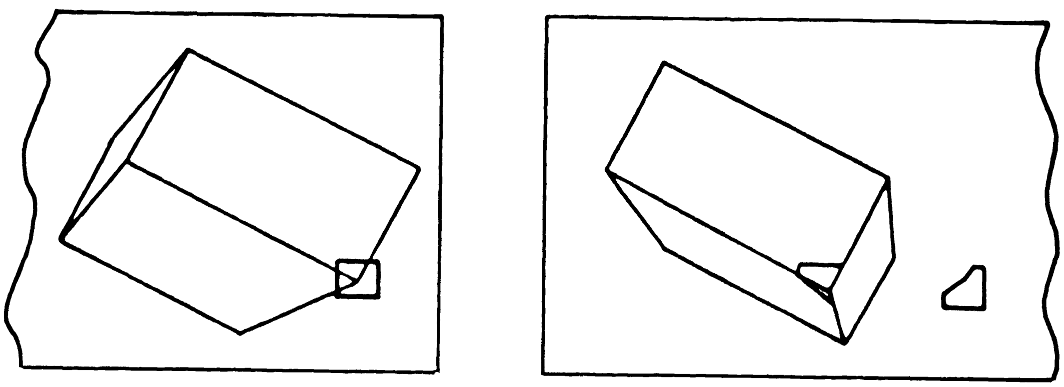


Fig. 1. Matching Areas Around a Vertex.

Design Concept

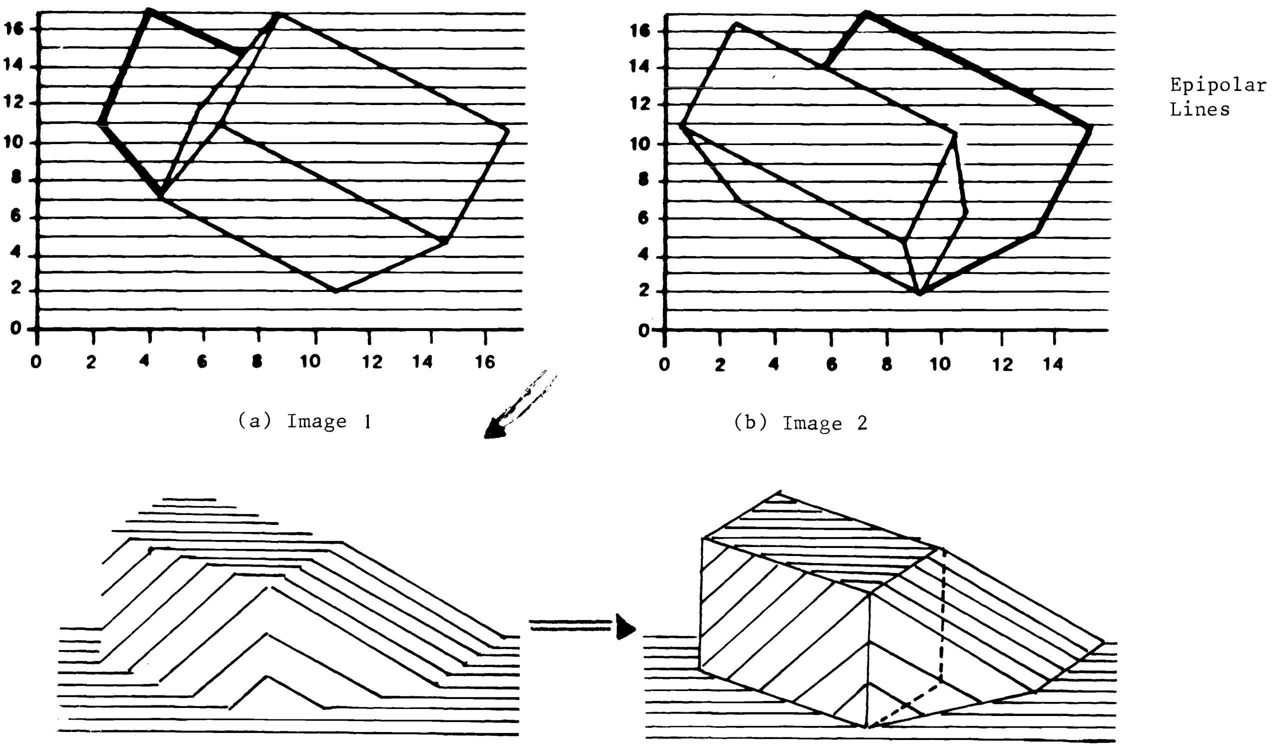
To deal with these problems, within a gray scale matching framework, it has been necessary to design an entirely new system, sructured to the features of planar surface sites. The design abandons both the tracking framework of traditional systems, and use of small area correlation. The system is known as an Automatic Planar Surface System.

This system rests on two fundamental concepts. The first is use of epipolar geometry to organize the problem. The second is specification of image matching in terms of Broken Segment Transformations.

Epipolar Geometry

The application of epipolar geometry in this problem is illustrated in Figure 2. Parts (a) and (b) of this figure show two views of a simple target. A set of "match lines," or epipolar lines, is overlaid. These lines correspond in pairs, indicated in the figure by identical numbering, one line from each image. A consequence of imaging geometry is that the matching problem can be solved separately for each epipolar line pair. That is, each line of a pair contains all match points for the other line. The matching problem is thus reduced to a one-dimensional search. The existence of such lines for the sensors of interest is proved elsewhere (2). We note here that orientation of these lines on a given pair of images depends on relative orientation of cameras forming the images, but not on scene geometry.

Suppose now that camera orientations are known, and that solutions are obtained to the matching problem on each epipolar line. The use of this information is illustrated in Figures 2-c and 2-d. By a process of intersecting three-space rays, matching solutions are transformed into a set of target profiles, such as illustrated in Figure 2-c. Each of these profiles corresponds to one of the pairs of epipolar image lines, and contains in fact just those portions of the target visible on the corresponding image lines. In form, the profiles are intersections of the target with uniquely defined "epipolar" planes. Alone, the profiles of Figure 2-c give only rough impression of target geometry. To obtain a recognizable form, planes can be fitted to these profiles and intersected. The result of this process is illustrated in portion (d).



(a) Image 1 (b) Image 2

(c) Profiles (d) Fitted Planes

Fig. 2. Conceptual Design of Automatic Planar Surface System.

The process summarized in Figure 2 is therefore as follows. From camera geometry, epipolar lines are identified on the input views. The matching system, the Broken Segment Matcher, then solves the matching problem separately for each conjugate pair of epipolar lines. An intersection step then translates the results into a set of 3-space profiles. Finally, the target geometry is recovered by fitting these profiles with planes.

Broken Segment Transformation

The key to the process described above is development of an algorithm to solve the matching problem on each epipolar line, for this is where the difficulty of dealing with cultural sites resides. The basic concept of approach to this problem is that of broken segment transformation.

The broken segment transformation is a graphical representation of matching points along conjugate epipolar lines. To illustrate, Figure 3 shows the broken segment transformation appropriate to the sixth epipolar line of Figure 2. Let X_1 describe position along the epipolar line in image 1, and $X_2 = g(X_1)$ denote, for each X_1, its matching position in image 2. Then the complete solution to the matching problem may be represented by the graph in Figure 3. This graph (or the function $g(X_1)$) is broken segment transformation. Its form, a series of straight line segments, reflects that of the corresponding three-space profile, and is a consequence of the fact that the target is composed of planes.

These transformations may be uniquely specified by giving (X_1, X_2) coordinates of the line-segment endpoints, and specifying connections between these points. The segment endpoints are called "breakpoints", and figure prominently in the discussions which follow.

The broken segment transformation provides a convenient representation of the problem features of planar surface sites. Abrupt changes in slope correspond to "breakpoints" while an occlusion corresponds to a horizontal or vertical segment. To exploit these characteristics, the matching algorithm is designed to search on each epipolar line for that Broken Segment transformation which best describes the scene. In this way, the difficult features of planar surface sites are incorporated as basic system design assumptions, and problems of applying terrain mapping techniques are by-passed.

The matching algorithm is called a Broken Segment Matcher. It is presented in the next section. A sub-

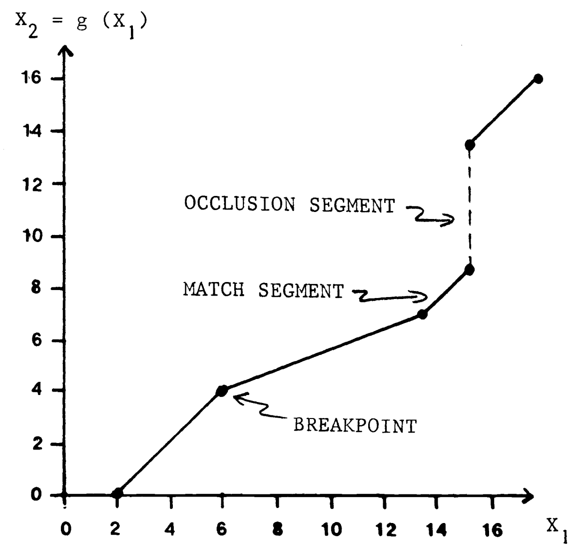


Fig. 3. Broken Segment Transformation. The transformation shown corresponds to epipolar line 6 of Figure 2.

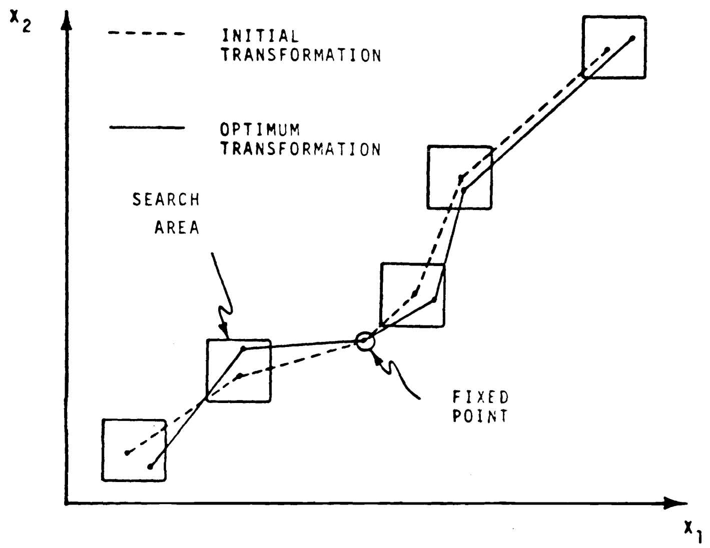


Fig. 4. Specification of a search with fixed number of breakpoints.

sequent section considers incorporation of this algorithm into the complete process defined above.

The Broken Segment Matcher

The problem is to build a Broken Segment Matcher, that is, an algorithm which will identify the broken segment transformation corresponding to each epipolar line on two views of a planar surface target.

The Broken Segment Matcher is designed to process the epipolar-line pairs sequentially, starting for instance at the bottom of the images in Figure 2, and progressing to the top. The reason for this design is evident on inspection of Figures 2-a,b. Each broken segment transformation is defined by its "breakpoints", which correspond to changes in slope of the target scene. In Figure 2, it is evident that, for most transitions from one epipolar line to the next, the number of slope changes intersected by the line does not change, and the positions of these slope changes alter only slightly. In other words, the number of breakpoints does not change, but breakpoint positions change slightly. Further, when the number does change, as when adjacent epipolar lines are on opposite sides of a vertex, the portion of the transformation affected is highly localized.

Accordingly, as the algorithm processes from line-to-line, only two basic functions are required. The first, and for most lines only, function is to adjust breakpoint positions slightly from one line to the next, leaving their number unchanged. The second function, specifically on encounter with a geometric vertex, is to change the number of breakpoints. The following subsections examine these functions separately.

The Fixed Point Number Search

The fixed point number search is specified as illustrated in Figure 4. The initial transformation (dashed line) is taken to be the transformation from the preceding epipolar line. It is assumed that the correct transformation on the current line can be found by altering these breakpoint positions slightly. The plan is to examine all transformations generated by moving breakpoints within "search areas" such as defined in the figure. A quality measure, or metric, is applied to each transformation of the class so defined, and the correct transformation taken to be that which gives this metric its best value. Accordingly, techniques are needed for exhaustive examination of this class, and for constructing an appropriate metric.

Exhaustive Search. The problem is to examine exhaustively a class of transformations defined by allowing each of N breakpoints to take ℓ possible positions about an initial estimate. (Image resolution is such that a continum need not be examined). Then ℓ^N possible transformations are allowed. Typically, $\ell \simeq 10$, $N \simeq 50$, so that this number is prohibitively large for direct search.

For this problem, however, an efficient search procedure can be defined. The procedure exploits the fact that any sensible metric for this problem must separate into independent contributions about a breakpoint which is constrained not to move. Although no such "fixed points" may be allowed in practice, any given point may be fixed temporarily during the search to simplify the procedure.

For instance, consider that breakpoint n (of N) is temporarily fixed, as illustrated by the third breakpoint in Figure 4. The "conditional" optimum for this case is found by combining separate optima to the left and right of n (so-called "left" and "right" conditional optima). Then the number of transformations examined is no more than $\ell^{n-1} + \ell^{N-n}$. However, if this calculation is repeated for all possible positions of breakpoint n, the desired unconditional optimum will be found. By this example, only $\ell(\ell^{n-1} + \ell^{N-n})$ transformations are examined. Of course, the searches to the left and right of n can be broken down still further. Efficiency results from the fact that transformation counts are added rather than multiplied.

Full exploitation of this fixed point effect is achieved by a recursive procedure based on "left" conditional optima. Details are presented in Appendix A of (3). The result is that the unconditional optimum can actually be found by examining only ℓ^2 (N-1) transformations, and further, that only one metric segment need be calculated for each transformation examined.

The importance of this procedure is that it permits computationally feasible access to the result of an exhaustive search. Thus, the optimum is a whole-line optimum in which the location of any point is influenced by positions taken by all other points on the epipolar line. In contrast, traditional correlation (for rolling terrain) fixes match-points on the basis of more local properties. This "non-local" character of the Broken Segment Matcher is important in dealing with local ambiguities of occlusion and featureless surfaces.

Metric. The metric is the quality measure which is to signify the correct transformation by taking an extremum. The fundamental concept is to provide a measure of the success of each transformation in matching points of similar gray shades. For an elementary formulation, let $f_1(X_1)$ and $f_2(X_2)$ be intensity functions (gray levels) along conjugate epipolar lines in images 1 and 2 respectively. The transformation class to be searched can be specified as $g(\underline{\lambda}; X_1)$, where $\underline{\lambda}$ is a vector of parameters. Let $\underline{\lambda}_o$ be the parameters describing the correct transformation, and consider an ideal "noise-free" case, in which each point of the target scene assumes the same gray level in both images. Then, the gray level functions must be related by

$$f_1(X_1) - f_2(g(\underline{\lambda}_o; X_1)) = 0 \tag{1}$$

Identification of $\underline{\lambda}_o$ will then follow from minimization over $\underline{\lambda}$ of a function

$$D(\underline{\lambda}) = \int dx_1 \, (f_1(X_1) - f_2(g(\underline{\lambda}; X_1))^2 \tag{2}$$

In realistic cases, where (1) does not hold exactly, minimization of (2) identifies a transformation satisfying (1) in a least squares sense.

As it stands, (2) represents only a "conceptual" formulation. However, it suffices to illustrate the most important metric feature, namely, that it supports the optimization procedure. In particular, (2) is trivially rewritten as a sum of separate contributions from each segment, and thus clearly splits into independent portions around any fixed breakpoint.

To construct a successful metric, certain modifications must be made. Consider first the occlusion. The metric (2) is undefined along any occlusion segment, since no match is defined by $g(X_1)$. To compensate, a penalty is assessed for each occlusion, proportional to the occlusion size. This procedure blocks a degenerate solution in which everything is occluded, and, significantly, makes the distinction of occlusion and match segments transparent to the optimization scheme.

The expression in (2) must also be reformulated to account for symmetry and for the smoothing and sampling processes which result in a digital image. This matter is treated in detail in Appendix B of (3). The result is that a proper metric includes filtering and windowing operations on the digital data.

Development of a suitable metric is a continuing research problem. Nevertheless, the metric described here provides the basic discrimination required, and has performed successfully in system tests.

The procedures defined in this section, for exhaustive search and metric formulation, comprise an elementary process which is sufficient to treat the epipolar lines in sequence, so long as the number of breakpoints remains unchanged. Separate tests of this process are reported in (3).

Breakpoint Addition and Deletion

The second major system procedure consists of techniques to accommodate changes in the number of breakpoints. These changes occur, as the algorithm processes from line-to-line, on each encounter with a geometric vertex. The focus of these techniques is on automatic breakpoint addition. Deletion of breakpoints appears as a by-product.

The strategy for breakpoint addition is as follows. On any given epipolar line, the process begins by invoking some cueing mechanism to suggest where new breakpoints might be found. This information drives specification of an appropriate search, with fixed number of breakpoints, and optimization of breakpoint positions by techniques described above. Results are then analyzed to determine if new geometric structures have been found. If not, the suggested breakpoints are deleted. If new structures are found, the appropriate new breakpoints are added to output of the matcher on the current line, and are used, just as "old" breakpoints, in formation of an initial estimate for the next line. The principal technical problems in implementing this strategy are developments of a suitable cueing mechanism and of appropriate analysis techniques.

Cueing. The principal cueing mechanism is identification of intensity edges in the input imagery. The motivation is that vertices (which require new breakpoints) usually correspond to strong gray level gradients or edges. Therefore, prior to the matching process, each image is analyzed separately, with in-house edge detection procedures, to provide a file of "cues" to the matcher. Techniques used to identify edges are described in Ref. 4.

Because it treats each image separately, this approach to cueing can have no direct tie to scene geometry (which is directly manifested only in distortions between two images). It thus introduces spurious "suggested" breakpoints associated with strong edges which have no geometric significance. Examples are cues derived from lines in parking lots, sidewalks, and edges around windows. These must be deleted in subsequent processing.

Analysis. During matching, edge information is incorporated on each line in the form of suggested breakpoints. These breakpoints participate in the optimization procedure. Results must then be analyzed to determine if any of these points correspond to a required breakpoint addition.

Because geometric vertices are only infrequently encountered, most of the suggested points will in fact be spurious. Many of these spurious points are readily deleted because they occupy redundant positions, that is positions on a straight line between two other breakpoints. However, because of image noise, some spurious points will take positions which appear significant on any given line. These points must be deleted by appeal to neighboring lines.

Deletion of redundant breakpoints is a relatively straightforward process, which serves also as the primary procedure for deleting established breakpoints as a vertex is passed.

The motivation for examining neighboring lines is that structures of interest tend to persist over many lines, while response to noise is random. However, the analysis is not simply a matter of averaging outputs over many lines, for such averages tend to be quite complex in terms of number of breakpoints. Current procedures are detailed in Appendix C of (3). Roughly speaking, the system examines statistics of a group of consecutive transformations to identify regions where new breakpoints are required. Then, only breakpoints in this region of the most recent line are actually incorporated into subsequent processing.

In summary, the procedure for automatic point number control is as follows. Prior to matching, the input images are analyzed separately for edges to cue the process. During matching on each line, these cues are incorporated in the form of suggested breakpoints which participate in optimization. After matching on any given line, the results are analyzed, both alone and in conjunction with results on a few previous lines, to delete any redundant breakpoints, and identify new breakpoints which must be added. Additional breakpoints found are then supplied to the output file, and incorporated into the starting estimates before processing begins for the next epipolar line.

Matcher Process Flow: The Two-Channel Organization

Processing in the Broken Segment Matcher is organized into two parallel channels, as illustrated in Figure 5. The first channel contains an elementary sequence of operations, which, operating alone, are

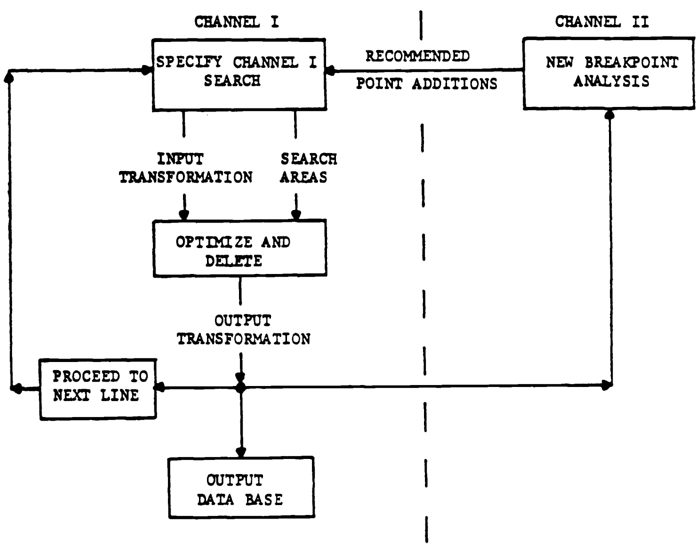


Fig. 5. Two Channel Organization.

sufficient to process the epipolar lines consecutively between geometric vertices. The second channel contains procedures for response to a vertex, that is, for detecting requirements for point addition.

Consider first the sequence in the first channel. The system processes the epipolar lines consecutively. The first step on each line is to derive an initial estimate for the transformation from the preceding line. A class of transformations to be searched is specified in terms of search areas defined for each breakpoint. (Recall Figure 4). The optimum transformation in this class is then identified. Redundant breakpoints are deleted, and the resulting transformation forms the system output on this line. Processing then proceeds to the next line.

The first channel, alone, has no capability to add breakpoints on encounter with a new structure. However, if new breakpoints are provided, when required, this channel contains all the capability required to process the scene. In a typical scene, in fact, most of the epipolar lines do not contain a vertex, so that processing in this channel is sufficient on most lines.

For fully automatic processing, new breakpoints must be supplied to the first channel system as needed. This is the function of second channel processing. This channel contains the full machinery for automatic breakpoint addition, as described above. On each line, it incorporates edge cues, carries out a search for optimum, and performs single and multi-line analysis to detect new breakpoints. It should be pointed out that the multi-line analysis is restricted to consideration of previous second channel results. Only when new breakpoints are well established by this procedure are they transferred to the first channel and incorporated into output processing.

Under ideal conditions, this second channel process will recommend breakpoint additions only infrequently, specifically when a geometric vertex is encountered. In this way, the first channel operates independently most of the time, and the combined process simulates a system with manual control over the number of breakpoints. In fact, results from this process compare favorably with these achieved under manual control[3].

This two-channel structure is specifically designed to isolate from the output channel all machinery for automatic point addition. The motivation is that point additions are only infrequently required, while the process for identifying them is extremely noisy. Incorporation of edge cues as candidate breakpoints provides transformations in the second channel with an enormous amount of flexibility during search for optimum. This flexibility increases the system response to noise in the imagery. In contrast, noise effects are suppressed in the first channel operation because relatively few breakpoints (only well established breakpoints) are involved. By separating these two processes, the system exploits this noise suppression in formation of the output, while separately admitting the flexibility needed to process automatically.

System Organization

Constructed according to this specification, the Broken Segment Matcher forms the heart of a system for automatic 3-D modelling of planar surface sites. Components of this system are configured to support operation of the Matcher, within the design concept illustrated in Figure 2. Process flow for this system is illustrated in Figure 6. A more detailed presentation is contained in reference (5).

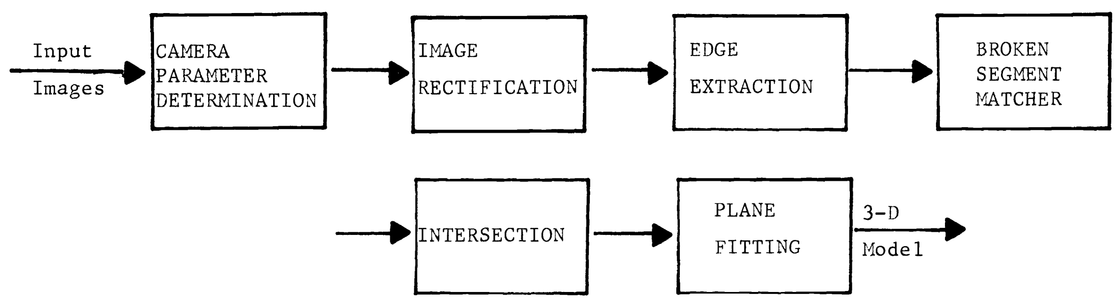


Figure 6. Automatic Planar Surface System: Process Flow.

Input is two views of a target site, the views being in digital form. Output is a representation of the site in terms of planes, edges, and vertices of a target model.

The first processing steps concern camera modelling. Relative orientations are derived for the imaging cameras, to support identification of epipolar lines. The images are then distorted geometrically so that epipolar lines line-up with the raster scan. This process is called "rectification", and simplifies data manipulations during matching.

The next step is to derive edges from the imagery to support cueing for automatic breakpoint addition. Edge detection techniques are applied to each image separately, and the results made available in "cue files" to the matcher.

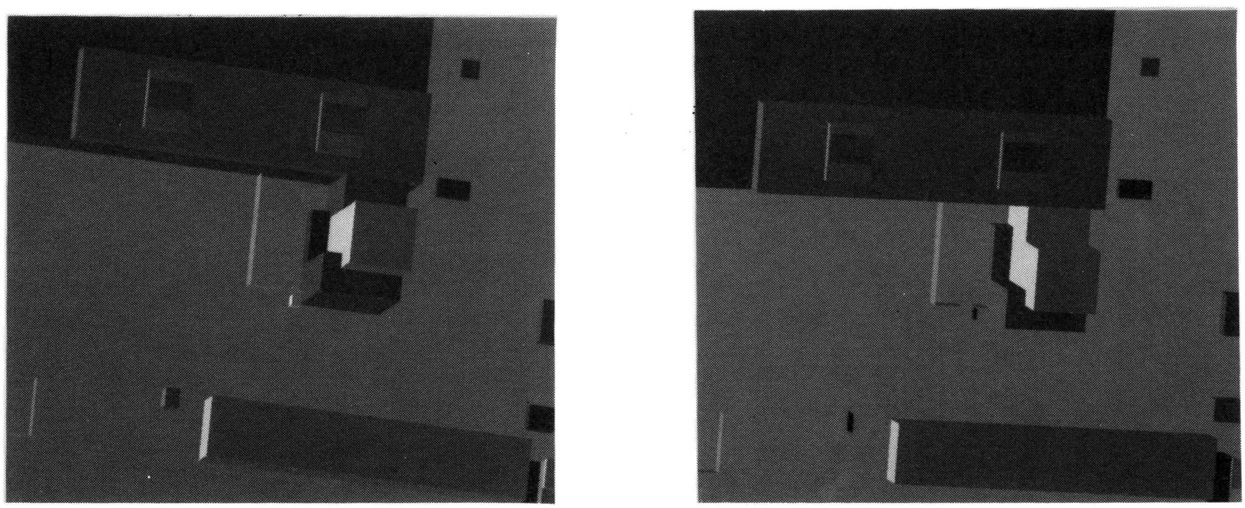
The next step is exercise of the Broken Segment Matcher. The algorithm is provided access to edge cues for both images, and to the input images in rectified form. Further, a broken segment transformation is specified on one epipolar line to start the process. In current versions, constraints are also provided on allowed slopes in the scene. After these inputs, processing by the algorithm is entirely automatic, and results in a specification of a broken segment transformation for each epipolar line in the scene.

The next step is to translate these transformations into a set of profiles of the target in three-dimensional space, as illustrated by Figure 2-c. This "intersection" step is a trivial algebraic operation once camera stations and broken segment transformations are known.

The final planned step is to fit these profiles with planes, as illustrated in Figure 2-d. This step is not treated in this report.

Test Results And Conclusions

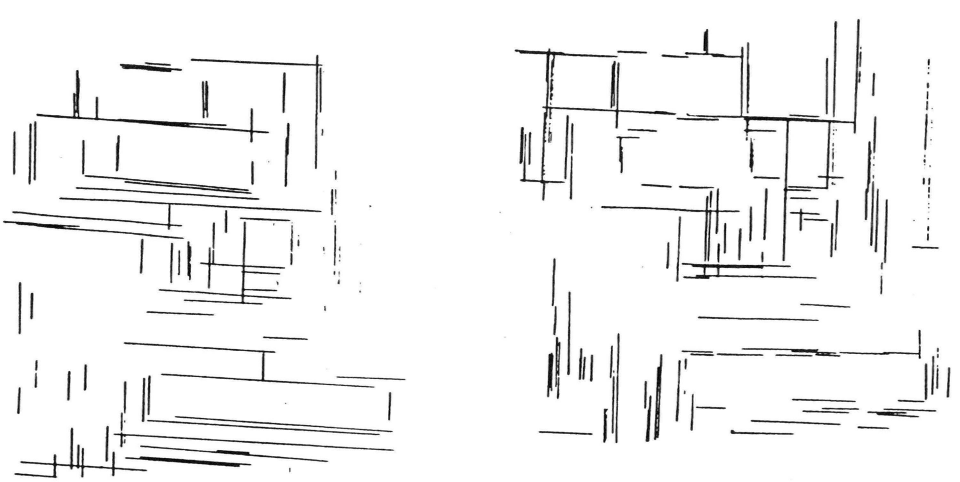
A demonstration of this system, through the intersection step, has been carried out on a realistic reconnaissance data set. Test data are treated in detail in Appendix E of reference (3). They consist of two views, of the Lockheed Building 104, Sunnyvale, California. These views have been derived by a reconnaissance sensor of the class expected to support an operational missile system. For display purposes, a block model of the site is used. This model, derived by manual measurement on the original data, can be analytically projected to any camera station. Projection to the input camera stations yields synthetic representations of the two input images, shown (after rectification) in Figure 7.



(a) Image 1 (b) Image 2

Fig. 7. Projections of Block Model of Building 104. Views Correspond to Rectified Form of the Two Views in the Input Data.

The first significant results (after rectification) are set of edges derived to support breakpoint addition. Edges derived from the input image are displayed in Figure 8. The noise evident in these results emphasizes that the test is conducted on real imagery, and not on the synthetic representations of Figure 7.



(a) Image 1 (b) Image 2

Fig. 8. Edge Results From Rectified Input Images.

After edge detection, the Broken Segment Matcher is exercised, and intersection performed on the results, yielding a set of target profiles in three-diemnsional space. To display this result, a two-dimensional projective view of the profiles is shown in Figure 9, beside a hand generated model of the building site.

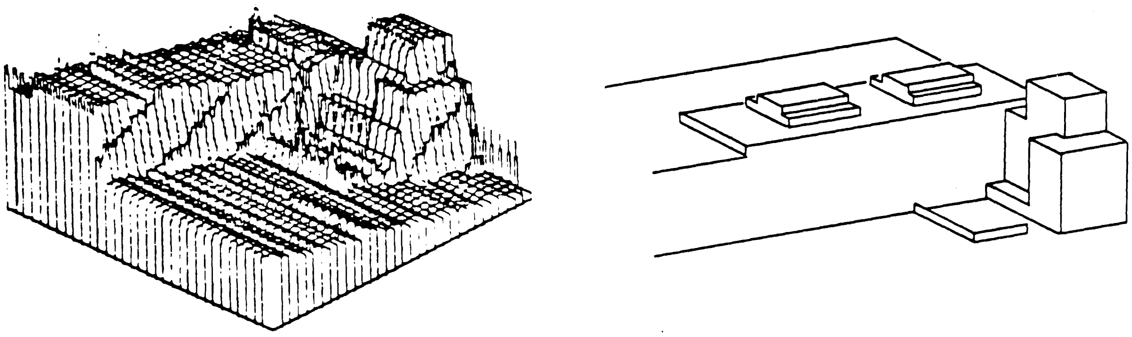


Fig. 9. Target Profiles Derived by Automatic Planar Surface System.

For interpretation, it is significant that the system has not gone through its final planned processing step, which is fitting of the profiles with planes (compare Figure 2). In this context, small scale noise evident in the results is not as significant as the fact that, in support of subsequent plane fitting, the system has captured broad outlines of the target structure.

For the case of targets composed of planes, these results demonstrate solution of the central problems of automated target modelling. The system has dealt successfully with discontinuities in the site. Indeed, abrupt changes in target slope are evident in the figure, and image occlusions were processed, in fact measured, to achieve the result. Further, the matching algorithm, which represents the most technically difficult component, functions entirely automatically, except for specification of starting parameters. The test thus constitutes the desired feasibility demonstration of automatic stereo measurement for this class of sites.

The ultimate objective of such work is development of a useful production level system for modelling 3-D geometry of cultural targets. At this time, it is expected that the hardware configuration of such a system will be much like that of terrain modelling systems currently under development.[1] However, considerable work is required in refinement and expansion of algorithm techniques.

In the techniques for planar surface sites, fundamental problems remain. It is still necessary to develop a successful algorithm for fitting planes to noisy target profiles. Within the Broken Segment Matcher, techniques must be developed to detect and resolve ambiguities in the gray level matching metric. Other areas for work with the matcher include development of reliability measures, more sophisticated incorporation of edge and region analysis of the input images, and development of iterative processing techniques. All of these efforts can be expected to improve model fidelity and enhance the stability of the matching process.

Development of techniques for more complex geometries is a more ambitious undertaking. Early investigations of this problem suggest that the line-by-line processing, which exploits epipolar geometry, may not be appropriate for these problems. In that case, development will require a break with the Broken Segment Matching approach which is as substantial as the break between this approach and "traditional" terrain mapping technique.

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