Video Rasterstereography: A Method for On-Line Measurement of Body Surfaces

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ABSTRACT: Rasterstereography (using a projected grid) is a method for three-dimensional measurement of body surfaces. Up to now precision measurements were only possible using film recording, because video cameras were too low in resolution. Recently, high resolution solid state video cameras became available. Thus, rasterstereography with on-line image processing is enabled, avoiding time consuming and cumbersome film development and scanning. In this paper the hardware design of a real video rasterstereographic system for medical applications (measurement of the human back surface) is outlined. The basic ideas of image data processing – as presented in earlier papers – did not change; however, some improvements in the software have been introduced, rendering the image analysis and three-dimensional surface reconstruction more reliable. At the same time, more elegant methods for calibration become available, which will be discussed in more detail in a subsequent paper.

INTRODUCTION

RASTERSTEREOGRAPHY IS A PHOTOGRAMMETRIC METHOD for measurement of body surfaces using structured illumination. Similar to common stereophotogrammetry, the underlying principle is triangulation. Therefore, accuracy and spatial resolution is basically equal to that of stereophotogrammetry, provided that photo-optical equipment of similar quality is used.

In the past, rasterstereographic precision measurements were only possible by using a conventional photographic camera and film registration (Frobin and Hierholzer, 1981). A major disadvantage was the necessity of film development and subsequent digitization in a scanner. This procedure is not only slow and circumstantial, but also susceptible to additional errors introduced by the geometry of the film scanner, by dust particles and scratches, and by film shrinkage and granularity. A substantial improvement can be achieved by using a video camera with on-line digitization. However, in the past video cameras with sufficiently high resolution were available only with vidicon type image tubes, exhibiting rather high, irregular, and time-variable distortion. High precision measurements are not possible with these devices. On the other hand, solid-state image sensors are virtually distortion-free, but up to recently, they were only available with rather poor resolution. An early application using a camera with 244 by 248 picture elements (pixels) was published by Docter and Ensink (1985). They obtained a depth resolution of 2 mm at a distance of about 2 m, which is not sufficient for most applications.

Recently, high and very high resolution solid state sensors have been developed. A commercial-grade CCD Camera with 1320 by 1035 pixels is manufactured by Videk (Kodak). Even this camera, though very expensive, is still much lower in resolution than a conventional 35-mm film camera. However, in many applications, particularly in rasterstereography, a resolution of 600 to 800 pixels per TV line is sufficient if smoothing and sub-pixel interpolation is employed (El-Hakim *et al.*, 1989).

An additional advantage of a solid-state video camera is that it is, by itself, a metric camera, because the pixel matrix defines a fixed intrinsic image coordinate system. Thus, no provisions for fiducial marks are necessary (Frobin and Hierholzer, 1985).

In this paper an application of video rasterstereography for measurement of the human body surface is presented. Using a medium resolution camera with 604 by 576 pixels, a depth resolution of 0.2 mm (after smoothing) is obtained. A high speed computer is necessary to perform image analysis and model reconstruction in a few minutes. This is essential for routine applications, for example, in medicine.

APPARATUS

The basic design of a system for video rasterstereography is largely similar to the system described by Frobin and Hierholzer (1981). In Figure 1 a schematic outline is given. The projector (Leitz Pradovit Universal 250 W) is equipped with a line raster diapositive RD (manufactured by Heindenhain, Traunreut). As described in our previous papers, the line numbers are encoded in the pattern of heavy and light lines. A line width relation of 40 μm to 60 μm for the light and heavy lines, respectively, was found to be optimal. (Note: a copy of the raster diapositive is available from Heidenhain on a written permission from us.) The camera contains a frame transfer sensor with 604 by 576 pixels (Valvo NXA 1011) and was manufactured by Innovationstechnik (Bremen). To make the best use of the sensor resolution, the camera is rotated by 90° ("portrait format"). The TV lines run, therefore, vertically and are consequently called columns of the pixel matrix.

The working distance of the system is D = 2 m. With a stereo base B = 0.8 m a convergence angle CA of about 22° is obtained. The density of the line raster on the body surface is 1 line per centimetre. Because the depth of field of the projector lens (*f*:2.5, 90 mm) is much lower than that of the camera lens (*f*:2.8, 16 mm), the optical axis of the projector is oriented horizontally so that the raster diapositive is approximately parallel to the body surface of a standing subject.

The spatial resolution of the camera at the site of the object is roughly 1 pixel per millimetre (horizontally and vertically). Thus, the body surface is sampled with a point density of about 10 points per cm. This is to be compared with the density of 1.5 points per cm formerly used in film rasterstereography. By using appropriate smoothing algorithms, the higher density is used to compensate for the lower resolution of the CCD sensor as compared to photographic film.

In Figure 2 the image data processing system is shown schematically. The camera is connected to an 8-bit video digitizer (Eltec PPI 1/2) in a VMEbus system. A single frame is stored in the video memory and can be directly accessed by the processor via the VMEbus. In principle, up to six frames (either consecutive or individually triggered) can be stored in the 2 Megabyte video memory. This feature is, however, presently not implemented in our software. A video monitor is directly connected to the digitizer, showing either the "live" video image (e.g.,

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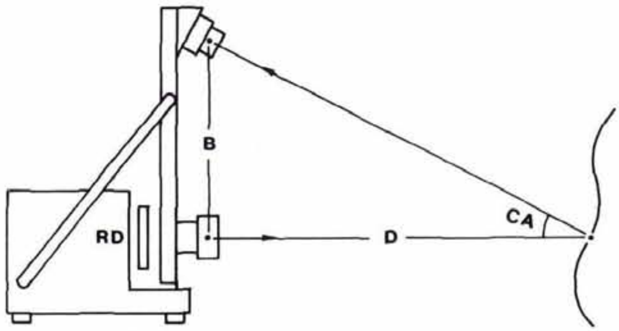

FIG. 1. Optical system for video rasterstereography.

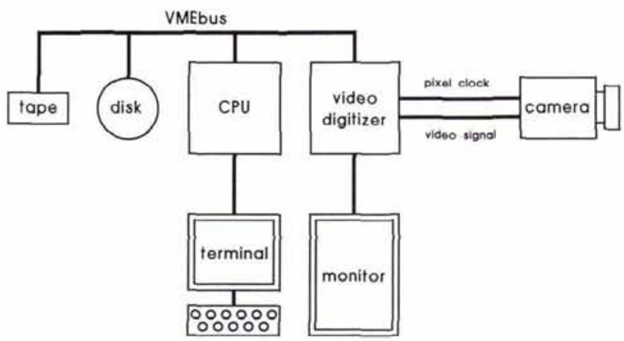

FIG. 2. Image processing system for video rasterstereography.

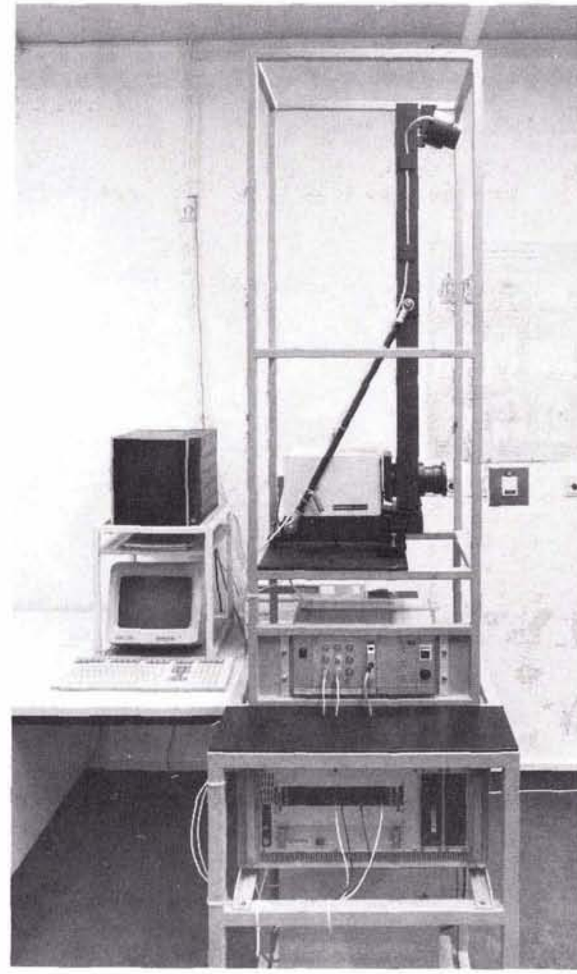

FIG. 3. View of the video rasterstereographic system.

during patient positioning) or the "frozen" image after recording. In addition, it is used to present control information (e.g., the reconstructed model surface).

A very important feature of the video digitizer is its synchronization to the external pixel clock of the camera. Only cameras with a pixel clock output and digitizers with a corresponding input are useful for video photogrammetry. Otherwise, a jitter of (at least) ± 1 pixel may result, which makes any sub-pixel interpolation impossible. Sub-pixel interpolation is essential to compensate for the still rather low resolution of the image sensors.

Another useful feature is the possibility to automatically adjust the digitizer gain and offset under program control. By that, the dynamic range (8 bit) can always fully be utilized without the risk of exceeding the linear range or impairing the signal to noise ratio.

The computer is a Motorola MVME 147 single board processor with a 68030 CPU and a 68882 FPU (both 25 MHz). The primary image data (pixel matrix) are stored on a Winchester disk and archived on a streamer cassette tape. A graphic terminal and a laser printer are used for system operation and data output. Figure 3 shows the complete system.

Because image data acquisition is completely independent of computer operation, a real time operating system is not required. Therefore, to take advantage of the extensive software base available, Unix V/68 is used. The major part of the software is written in FORTRAN 77, with only a few program modules written in C. The latter are necessary to access the video memory in the digitizer via the shared memory mechanism of Unix V/68. Because FORTRAN 77 (SVS F77) proved to be slightly faster than C, no attempt was made to speed up the programs by using another language.

IMAGE PROCESSING

Once the video image is digitized and stored in the computer memory, subsequent image processing is essentially identical to the procedures described earlier for conventional rasterstereography (Frobin and Hierholzer, 1983a; 1983b). Some modifications and improvements have, however, been introduced to take full advantage of the information content of the video image. Image processing is broken into several steps which are briefly outlined in the following sections. These steps are called peak detection, line search, line sequence analysis, and line numbering. Thereafter, three-dimensional model reconstruction is possible.

PEAK DETECTION

Because the camera is oriented in portrait format, the TV lines (i.e., columns of the pixel matrix) intersect with the raster lines running approximately horizontally. Consequently, in a pixel column every raster line forms an intensity peak which is approximately Gaussin-shaped (Figure 4). The height or, more exactly, the area of the peak is a measure of the intensity of the raster line. The distinction of light and heavy lines is based on the peak area. The location of the peak is determined by sub-pixel interpolation from the relative intensities of the pixels belonging to the peak.

The most difficult task is to determine the pixels belonging to a particular peak. This is carried out by searching for intensity steps in a pixel column which have sufficient height and slope.

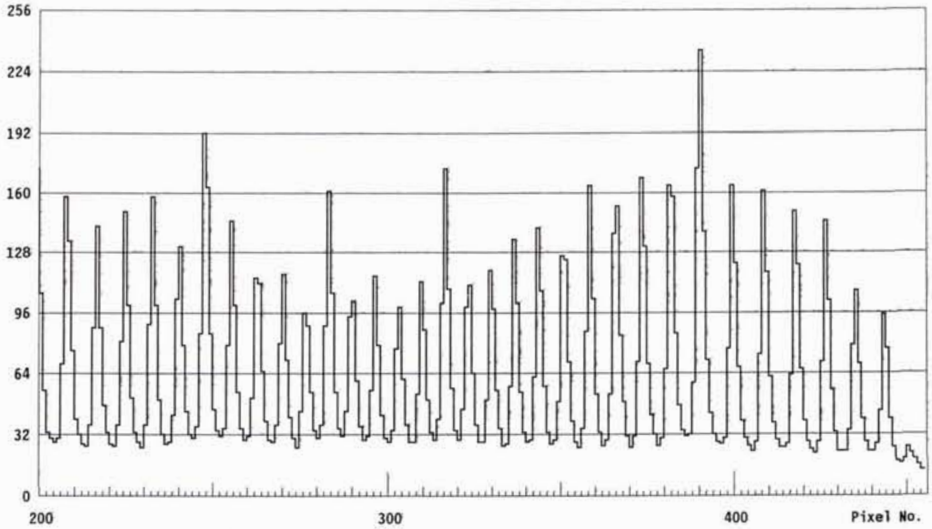

FIG. 4. Intensity distribution in a section of a pixel column (tv line).

A peak is formed by a sequence of a positive and a negative slope in a proper distance. The interpolated location of the peak is then calculated by fitting a Gaussian function to all the pixel signals belonging to the peak, *i.e.*, from the intensity minimum left of the peak intensity to the next minimum right of the peak (Figure 4). In order to reduce noise and to improve the localization accuracy, a certain bias is subtracted from the pixel intensities. Fitting of a Gaussian function is simply effected by calculating the intensity-weighted mean of the pixel locations (first-order moment of the intensity distribution). The resulting accuracy of the peak coordinate is on the order of 0.05 pixels. Because one pixel width corresponds to roughly 1 mm at the object site, the lateral and depth resolution of the measurement is on the order of 0.05 and 0.13 mm, respectively, under optimum conditions.

This procedure proved to be superior as compared to the method described by Frobin and Hierholzer (1983a), where the mean of the left and right slope coordinate was taken as the peak coordinate. In that case, rather large aliasing errors due to the limited resolution of the sensor were observed (Frobin and Hierholzer, 1989).

LINE SEARCH

In the line search procedure, the raster line peaks found in different columns of the pixel matrix are reconnected to continuous lines. As outlined by Frobin and Hierholzer (1983b), this is based on neighborhood relations between raster line peaks in adjacent columns in the image matrix.

Some improvements have been introduced in order to make the line search more reliable. In some cases, false interconnections between actually different raster lines occur. Because in a certain sense, line search is already a part of image interpretation (scene analysis), the optimum strategy depends on the application, i.e., on the type of surfaces to be measured.

In the case of the human body, one is concerned with irregular, but smooth, surfaces. Therefore, the projected raster lines are likewise smooth, and a sharp corner in the sequence of raster line peaks is an indication of a false interconnection. The line must then be dissected according to a smoothness criterium.

In some instances, however, the peak sequence is continuous and smooth even though a false interconnection occurred. This may happen in the case of sudden depth modulations of the surface, e.g., at the shoulder blade in Figure 5 (arrow). In that case, the smoothness criterium is insufficient and, from the locations of the raster line peaks alone, no objective decision is possible as to whether and where the line should be dissected. Thus, additional information is needed to solve this problem.

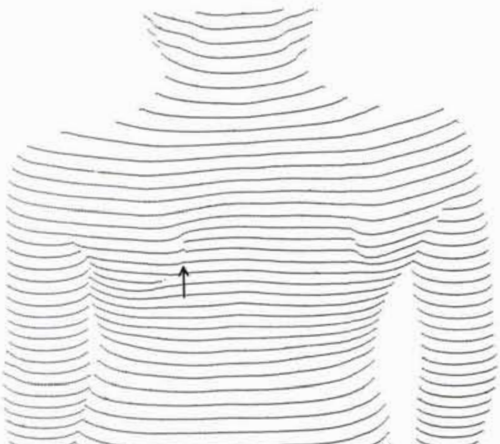

FIG. 5. Result of peak detection with false line interconnection (arrow).

As Pekelsky (1986) noted, the magnitude of the local surface gradient is related to the (relative) light intensity reflected off the surface. At locations of steep inclination (high gradient) the intensity is low. In the case of video rasterstereography, the light intensity is encoded in the peak area. In Figure 6 (top) the peak area A (= intensity) and the y coordinate (bottom) of a selected raster line (see Figure 5, arrow) is plotted. The boundaries between the arms and the trunk are marked by pronounced intensity minima which coincide with the corners in the raster line. Moreover, at the location of the false interconnection (arrow), a distinct intensity minimum is observed. This minimum results from the high surface gradient at the shoulder blade. Here the line is to be dissected. Generally, sudden changes of the surface

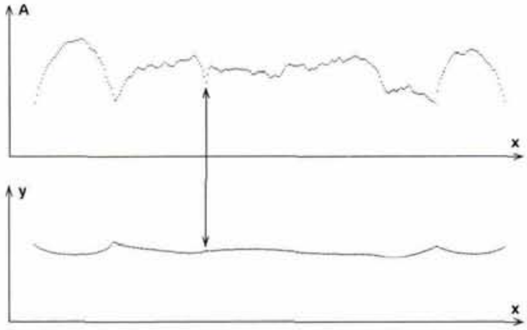

FIG. 6. Intensity distribution (top) of a raster line (bottom) with a smooth but incorrect interconnection (arrow).

gradient and, hence, of the intensity indicate those regions where "texture errors" of the raster line system are likely to occur.

In principle, all these locations may be detected from the intensity modulations along the raster lines. For this purpose, standard image processing algorithms such as the Laplacian operator are generally used. However, this procedure required a considerable computing time and—due to noise—delivered unreliable results. Much better results were obtained by using a hierarchical approach. In such a procedure, the raster lines are built up starting with the line portions of highest intensity. Using a lower intensity threshold, the existing line portions are allowed to grow by dilatation. In the next step, new lines with lower intensity are investigated and dilated with the next lower intensity level, and so forth. Because dilatation does not include connection of already existing lines, false interconnecitons are securely prevented.

This strategy is very much like solving a puzzle: the lines are built up according to the rules of maximum probability, using the most likely parts first, looking for best-fitting continuation parts, and deferring questionable decisions to a later time. Thus, wrong decisions are rendered extremely unlikely.

LINE SEQUENCE ANALYSIS

In the line sequence analysis the raster lines, which have been built up in the line search procedure, are arranged according to their natural topological order. This is a prerequisite for the correct identification and numbering of every raster line. This, in turn, is necessary for three-dimensional model reconstruction.

The line sequence analysis is based on neighborhood relations between entire raster lines. The procedure is, to some extent, similar to line search. However, instead of sequences of raster line peaks, sequences of complete raster lines must now be established. That is, image analysis is continued on a higher hierarchical level. Because of this analogy similar texture errors—now in the network of raster lines—may occur.

Generally, two consecutive raster lines in the diapositive delimit a stripe on the back surface which corresponds to two neighbored lines in the rasterstereograph. This may, however, not be true in the case of missing line portions or interruptions of the line sequence, leading to contradictory line numbers if different parts of the raster line system are considered.

In this case, a hierarchical approach is likewise suited to eliminate errors. According to this method, ordering of the raster lines is started using the longest lines with maximum length of mutual neighborhood. Proceeding to shorter lines, the line system is built up in a top-down scheme. Because every line is classified only once, contradictory ordering and hence wrong line numbering is securely avoided.

In Figure 7 the result of the line sequence analysis is shown. The stripes represent valid ranges of neighbored raster lines

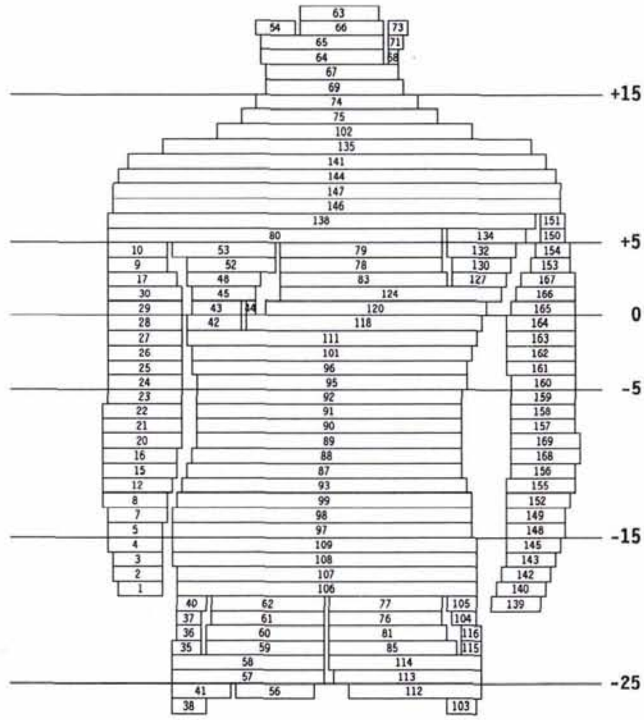

FIG. 7. Result of the line sequence analysis and line numbering (back projection into diapositive plane).

corresponding to real surface strips (the small numbers are reference numbers for the computer program).

LINE NUMBERING

As can be seen from Figure 7, the line sequence analysis delivers the correct ordering of the lines according to their relative position in the raster diapositive. The absolute line number may then be determined by adding an offset to the relative line number. The offset is determined from the location of light and heavy lines in the line system (for details, refer to Frobin and Hierholzer (1983b)). In Figure 7 the bold numbers on the right side indicate the absolute raster line numbers in the diapositive.

RECONSTRUCTION

From the locations of the raster line peaks in the image sensor plane and from the pertinent absolute raster line number, stereo image pairs of the raster line points can be calculated. Three-dimensional model reconstruction is then possible according to standard photogrammetric methods. A faster implementation is, however, possible by direct calculation of the spatial intersection of a ray passing through the camera nodal point (projection center) and the raster line point in the sensor plane with the light plane which is defined by the nodal point of the projector and the appropriate raster line in the diapositive (Hierholzer and Frobin, 1989). If lens distortion is to be accounted for, the light plane is deformed into a cone-shaped surface, and the intersection equation must be solved iteratively.

CALIBRATION

Calibration is performed according to well-known photogrammetric methods by using a control point system. Special procedures adapted for rasterstereography have already been published in previous papers (Frobin and Hierholzer, 1982a; 1982b; 1983a; 1983b). A particular additional advantage can be derived from the fact that the video image is pixel-synchronously digitized. Several image frames taken at different times can, therefore, be exactly superimposed by computation. By that, image segmentation is considerably facilitated. In Figure 8 a control point system is shown which is designed particularly for that purpose. It consists of a solid base made of cast aluminum. The control planes, bearing seven control points each, consist of aluminum plates which can be mounted at two different height levels by using columns of different length. The control points are holes underlaid with black velvet. The aluminum surfaces are sandblasted to obtain diffuse reflection of the projected raster lines. The accuracy of the control points is estimated to be better than 0.03 mm.

Several recordings of the control point system are taken with different arrangements of the control planes. In Figure 8 a particular configuration of the two existing planes is shown. At each of three possible lateral locations a "high" and a "low" position of the control plane is used, and each is recorded with the projector on and off. Thus, a total of six frames is recorded, three of which (projector off) are used for measurement of the control-point coordinates. The other three (projector on) are used for measurement of the raster lines. Hence, image segmentation is partially effected by storing the image information in different frames.

Details of the calibration procedure will be published in a subsequent paper.

RESULTS

The system described here was optimized for clinical measurement of the back surface of patients with scoliosis and other deformities of the spine. The practical use of such a measurement depends heavily on the immediate availability of the data. With the present equipment, a total time of about 90 seconds is needed for image analysis and surface reconstruction of a medium-sized subject. About 25,000 raster line peaks are detected in the original image. Using a simple linear smoothing algorithm, these points are reduced to one-third in order to reduce noise and to accelerate data processing. The resulting data points (about 8,000) are used for surface shape analysis and medical diagnosis, which is described elsewhere (Drerup and Hierholzer, 1990).

The primary accuracy of the reconstructed surface points on the human body surface was found to be in the order of 0.5 mm perpendicular to the surface (z coordinate). Using a surface interpolation and smoothing algorithm which is also needed for curvature analysis, the mean z coordinate error is reduced to 0.2 mm (Hierholzer and Frobin, 1989).

With the present design of the image processing algorithms, more than 1200 video rasterstereographs have been correctly reconstructed without a single error in the line pattern analysis. Thus, video rasterstereography has proved to be a fast, accurate, and reliable method for on-line measurement of irregular surfaces. Future improvements are still possible with respect to computing time and accuracy by using faster computers (e.g., RISC) and high-resolution image sensors. Also, the sampling density of the raster lines may be increased, in which case, however, more sophisticated image processing methods would be necessary.

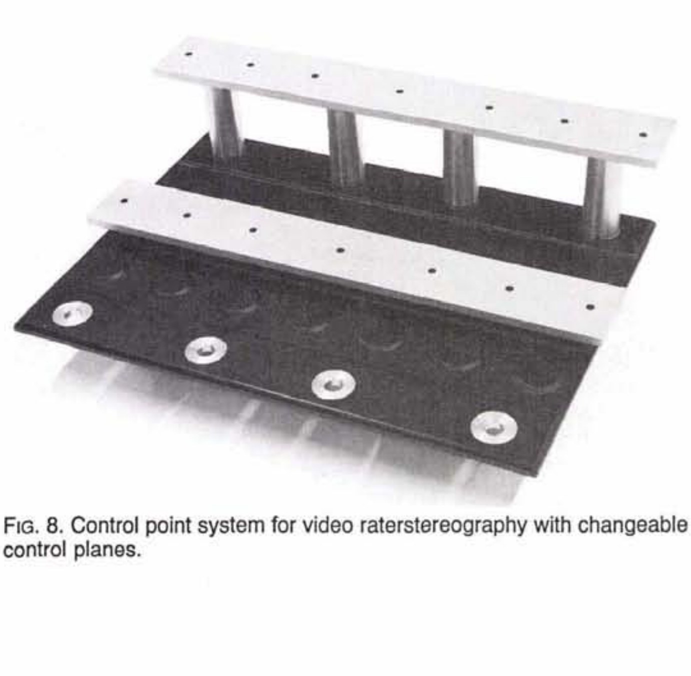

Fig. 8. Control point system for video raterstereography with changeable control planes.

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