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AUTOMATED KNOWLEDGE-BASED SYSTEM FOR STEREO VIDEO METROLOGY

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ABSTRACT: A knowledge-based system has been developed to help inexperienced users make measurements from stereo video images. The purpose of the system is to automate much of the routine functions and decision making in photogrammetric measurements on a personal computer (PC). The system can perform the following functions: (1) Check the validity of the input data; (2) warn of weak geometric conditions; (3) provide guidance, diagnostics, and counseling during success and failure modes; (4) conduct robust blunder detection; and (5) perform accuracy analysis through error propagation. The result was the development of a user-friendly vision system that can be used productively without in-depth knowledge of photogrammetry. Experimental results showed that the PC-based vision system achieved a potential accuracy of about one pixel on the image plane for planar coordinates. Lower measurement accuracy in the range of 4–5 pixels was obtained for the depth direction because of the intersection geometry and accuracy limitations in manual image matching. The statistical analysis scheme, based on random error propagation of the image coordinates, was a realistic accuracy estimator. Calculated three-dimensional (3D) measurement errors consistently fell within three times the estimated standard errors (3σ). Comparison with actual survey measurements showed that distances could be measured with an accuracy of better than 2 pixels, while volume and surface area were measured to within 3%. Image scale, base/object distance ratio, number and distribution of control points, and accuracy limitation in manual matching had a significant impact on the measurement accuracy.

INTRODUCTION

Methods of stereo photogrammetry have been developed to perform three-dimensional (3D) surface measurements. Major advantages of these methods include: (1) Potentially high geometric accuracy; (2) no contact required with the object being measured; and (3) provision of a permanent photographic record of the object (Bouazza 1992; Schneider and Sinnreich 1992; Miloshev 1992). Their major limitations include: (1) Time delay due to film processing and manual measurement; (2) high cost of special equipment such as cameras, stereoplotters, and/or comparators; and (3) need for a high level of expertise in both data collection and processing. Computer vision systems; i.e. computer-based systems, in order to quantify surface measurements, equipped with charge-coupled devices (CCD) and frame grabbers, have the potential to overcome some of the problems of film-based cameras for photogrammetric applications (Ho 1984; El-Hakim 1989; Jansa and Trinder 1992). In fact, they can provide real-time imaging acquisition capabilities without reliance on expensive scanning and conventional measurement equipment. Low-cost CCD video cameras, called camcorders, are fast becoming as common a household item as 35-mm cameras. The excellent geometric fidelity

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J. Surv. Eng. 1996.122:47-64.

of these cameras, coupled with their low cost and ease of operation, make them ideal tools for metrology applications (Wong and Obaidat 1992). Measurement accuracy better than one picture element (called pixel) at the focal plane is now routinely achieved.

Video camcorders, frame grabbers, and personal computers form the basic components of a video photogrammetric measurement system. These components are widely available in scientific laboratories and engineering offices. Simultaneously, research has shown that accurate geometric measurements can be performed using these systems. Among applications of computer vision systems are manufacturing, quality control, and gauging. An object to be measured is imaged from two different positions; i.e., to have stereo images for a common scene. By knowing the interior geometry of the used camera (or cameras); i.e., calibration parameters, a simple projective transformation procedure from image coordinates to ground coordinates is performed in order to quantify the object-space coordinates. The set of equations used for this task is shown in the Appendix I. The major obstacles to the common adaptation of such systems for stereo photogrammetric measurements are the lack of a practical method of camera calibration, and a user-friendly software package that does not require in-depth knowledge of photogrammetry from the user. Proper calibration of the interior geometry of CCD cameras is the key to computer vision metrology.

When a PC-based vision system is used, certain requirements should be met, including the ease of use, accuracy estimates using the error propagation concept, and accuracy compatible with conventional surveying.

Proper applications of photogrammetric techniques also require an expert to perform the following functions: (1) Consulting during a failure based on knowledge of technical rules and facts; (2) analyzing the data to determine the accuracy of the measurement; (3) decision making for the acceptance or rejection of measurements; and (4) educating inexperienced users with information concerning photogrammetric techniques. Thus, the "why," "when," "what," and "how" questions will be answered from the experience of the photogrammetric expert.

Expert knowledge is vital in photogrammetric data processing and analysis. Thus, applications of artificial intelligence and knowledge-based systems to these tasks have the potential of inducing more users to employ photogrammetric methods for measurements. Photogrammetric knowledge-based and expert system applications rely on both mathematical modeling and heuristic ("if . . . then") rules (Kretsch 1988). Thus, knowledge-based systems for photogrammetric analysis are hybrid systems (Sarjakoski 1988). The key to problem solving here is to represent the knowledge directly in the form of mathematical models and equations (deterministic). The rules and the facts for the knowledge-based system are needed to support the solution of photogrammetric equations. Development of a rule-based system as part of a heuristic knowledge base is a bottleneck in this domain.

This paper reports on the development of a convenient stereometric; i.e., use of stereo images to extract metric measurements, PC-based measurement scheme for video-based close-range photogrammetry applications. The scheme utilizes a human operator to perform the image recognition tasks. It is supported by a knowledge-based system for data processing and analysis, and algorithms to perform much of the routine functions of photogrammetry, enabling users to perform 3-D metric measurements using a video-based vision system.

J. Surv. Eng. 1996.122:47-64.

FUNCTION AND STRUCTURAL OPERATIONS OF KNOWLEDGE-BASED SYSTEM

A knowledge-based system has been developed to help users make measurements from stereo video images. The following functions are the core of the knowledge-based system:

1. Robust estimators for blunder detection. The measured parameters are assigned a weight equal to the inverse of the residual errors. Thus, observations with larger residual errors are given a proportionally smaller weight in the solution.
2. User consultation in the case of failure during data processing and analysis through use of "if . . . then" knowledge rules and standards facts. It will also provide possible explanation and solution for an error mode.
3. Statistical accuracy analysis scheme for 3-D measurement based on error propagation. The scheme is based on the assumption that errors in the computed object point coordinates arise solely from the propagation of random error in the photogrammetric measurement.
4. Assistance in decision making to accept or reject the results based on a selected global accuracy criteria.

The knowledge-based system has been incorporated into a PC-based software package, called DR-STEREO, which consists of the following four modules: measurement module, relative orientation module, absolute orientation module, and camera calibration module.

A set of rules for the foregoing modules was developed. The rules and facts are based on photogrammetric principles. The hypothesis for the performed task is normally given during the software execution for any particular step. Under each hypothesis, there are rules and facts based on the concept of that hypothesis. These rules are checked during the different operational steps. If during the data-input or any data-processing stage an error arises, which does not comply with these rules, a diagnostic message appears on the screen and in an output file for the user to consult for further information. The user is then asked to take action based on the knowledge-based diagnosis. Questions such as, "why did the knowledge-based system suggest this?" and "what action should be taken to solve this problem?" can be answered through an interactive dialog with the menu interfaces.

The knowledge-based system has been divided into three stages: (1) data input; (2) data processing; and (3) result analysis and decision making.

Specific tasks for the system include the following.

Data Input Check

The system checks, self-diagnoses, and in appropriate situations corrects errors for the following: even distribution of image points in stereo images; user faults in data input and in stereo image positions; control distribution; ground and image coordinates system; and warning on weak geometric conditions. Knowledge-based algorithms were developed to check the integrity of the input data.

Data Processing

The system provides guidance and counseling in a failure mode during data processing. The user involvement in this task is reduced by providing the following: (1) automatic blunder detection through robust estimators, i.e.,

J. Surv. Eng. 1996.122:47-64.

estimators that are relatively insensitive to limited variations in the frequency distribution function of measurements, and data snooping, i.e., reducing the weights of weaker observations by assigning new weights based on their residuals; (2) automatic convergence of the iterative solution; and (3) rejection of measurement with large residual errors. A set of heuristic "if ... then" rules, based on mathematical models and photogrammetric principles, was developed to assist inexperienced users perform data processing within the developed software package.

Data Analysis

A rigorous statistical method has been implemented to check and evaluate the computed 3D coordinates. The analysis is based on error propagation. The results are used to provide guidance to the user on the quality of the computed coordinates and on the acceptance or rejection of computed results. The following points form the core of this task: (1) performing accuracy analysis through error propagation; (2) extracting 3D coordinates and their precision; (3) identifying unknown parameters and their variance-covariance matrix; (4) computing data input residuals and their root-mean square (RMS); (5) providing suggestions to enhance the results based on the input data used; and (6) providing decision-making criteria for the acceptance or rejection of both the input data and the computed 3D coordinates based on global rejection criteria.

The system has a potential to detect errors, diagnose, and counsel in the failure mode situation in the foregoing cases.

Detected errors in this knowledge-based system are divided into two types:

Errors

These are major errors that will affect the final results and the solution will not recover the final answer unless the requested actions recommended by the knowledge-based system are undertaken.

Warning

These are counseling messages to recommend user action to further enhance the results. Thus, the results will be enhanced if these directions are followed.

In addition, the informative-type message has the function of informing the user of what hypothesis the system is pursuing at that moment. This message needs no action from the user. The informative messages will give the general user, who has no in-depth knowledge of photogrammetry, the potential to follow-up and understand these functional operation and tasks.

Knowledge-Based Rules

The knowledge-based rules were classified into: type 1 rules (i.e., errors) and type 2 rules (i.e., warning and informative messages). These rules are listed as follows.

Type 1 Rules

1. The x-coordinate of an image point in the left image should be larger in value than the x-coordinate of the conjugate point in the right image; i.e., the left image of the stereo pair should be placed on the left display window during image coordinate measurement.
2. Both the left and right images must have the same array sizes; e.g., 512 $\times$ 512 pixels.

J. Surv. Eng. 1996.122:47-64.

3. A minimum of five pairs of conjugate image points are needed for relative orientation.
4. The image coordinates must follow the convention established by the software package. The origin (0,0) can be located at the upper left corner or at the center of the image, with the x representing the columns and increases to the right and the y representing the rows and increases toward the bottom.
5. The object-space coordinates must be right-handed, with the Z-axis being vertical and the X-Y plane being horizontal.
6. Computed standard error of unit weight should not be larger than two times the a priori standard error of unit weight.
7. A solution for absolute orientation requires at least two known horizontal control points and three vertical control points.
8. For camera calibration using planar constraint, the approximate object-space coordinates of four points on the plane and the length of one line must be provided.
9. For camera calibration using planar constraint, each quarter of the stereo model should have at least four measured image points. There should be at least 35 measured image points in the stereo model.

Type 2 Rules

1. Each of six regions within the stereo overlap area of each image should have at least one image point for the purpose of relative orientation. Further, no region should have more than three times the number of image points in any of the other regions.
2. Separation between the two camera positions should be larger than 0.5 m.
3. The two images of a stereo pair should overlap more than 60%.
4. An image point is rejected from a solution if either its x- or its y-residual exceeds three times the computed standard error of unit weight.
5. If an iterative least-square solution fails to converge after a specified maximum number of iterations, the convergence threshold is increased by 20%. This process is repeated until the convergence threshold reaches a specified value, such as 0.1 pixel. If the solution still fails to converge, results from the last iteration are provided as output with an error message.
6. Convergence threshold should have a value between 0.001 and 0.1 of the a priori standard error of unit weight.
7. Computed standard error of unit weight should start to decrease no later than the fifth iteration.
8. Good data usually result in convergence by the 20th iteration.
9. In relative orientation, the computed estimated standard errors should not exceed $\pm 2°$ for rotation angles and ± 3 cm for positions of exposure centers.
10. For absolute orientation, each quarter of the stereo model area should have at least one control point, and no quarter should have more than three times the number of control points in any of the other three quarters.

J. Surv. Eng. 1996.122:47-64.

11. For absolute orientation, the control points should not all lie on a plane.
12. Object-space coordinates of a control point are rejected from a solution if the residual of any of the three coordinates (X, Y, Z) exceeds three times its estimated standard error.
13. In absolute orientation, the estimated standard errors for the computed parameters should not exceed the following: Rotation angles—$\pm 0.5°$, translation parameters—± 3 cm, and scale factor—± 0.001.

KNOWLEDGE IMPLEMENTATION

The error messages appear on both the monitor screen and in an activated file. The user can follow-up on activities that occurred during the execution of a certain task. An alarm of three long beeps is given for an error, while an alarm of two beeps is given for a warning. If an error occurs, the task will be terminated and the program will provide the user an opportunity to fix the errors based on the system's instructions. On the other hand, if a warning occurs, the system will give the user a chance to fix the problem according to the dialog with the knowledge-based system during the task execution. Specific values for the error and accuracy thresholds are based on literature information and the writers' experience.

The user is directed to execute certain tasks according to the error type. Some errors require the user to change some of the input data, and the errors in processing and analysis will be solved by the system automatically without user involvement.

For each rule of a certain task in a given module, the following list is normally provided through the system: (1) Hypothesis; (2) rules and facts; (3) type of errors; (4) error messages; (5) reasoning (answers to "why" questions); and (6) priority solution (give solutions to the questions to be asked in a priority order). The hypothesis represents the basic concept of the following detailed rules. The rule and facts represent detailed logic for the hypothesis. The error message appears on both the computer screen and in the activated data file for error detection and warning. The "why" and "what" questions can be asked by the user to obtain answers from the knowledge-based system for the problem that has arisen. The rule order is important to follow during the knowledge-based instructions.

The knowledge-based system was successfully tested during data processing and analysis in both success and failure modes. The system was evaluated successfully for detecting errors in the input data, systematic error modeling, robust estimators for gross error detection, failure mode recovery during data processing, guidance in processing, and for assisting the interpretation of results through a statistical scheme. The demonstration and test were done for several sets of input data. Basically, the user involvement in data reduction and data analysis was minimal.

The capability of the knowledge-based system, combined with the interface to the PC-based measurement system and a convenient camera calibration scheme, shows the potential for the user-friendly video measurement system.

SOFTWARE DEVELOPMENT

A software package called DR-STEREO was developed to support video metrology measurements on a PC. The package includes a series of computer programs to facilitate this research. Computational algorithms and computer

J. Surv. Eng. 1996.122:47-64.

programs were developed for stereo image display, subpixel determination of image points, camera calibration using a planar object, relative orientation, absolute orientation, computation of 3D object space coordinates and by-product surface parameters and their precision, statistical analysis scheme for 3D measurements, data-management system using point or continuous (string) mode, and implementation of a knowledge-based system for data processing and analysis.

DR-STEREO provides a display window of 300(H) × 260(V) pixels in 16 different colors for each of the two stereo images. Different portions of the two images can be displayed on the user command, with no limit on the array of the digital stereo image. A point cursor, consisting of a single red pixel, is provided for pointing in each of the two display windows. The two cursors can be made to move either together or separately. A subpixel accuracy measurement of image points can be done by activating a zoom-in function by pressing a command key. Thus, a manual point matching for conjugate image points can be performed easily.

EXPERIMENTAL STUDIES

Equipment

Fig. 1 shows the hardware configuration of the off-the-shelf PC-based vision system used in this study. The system was a part of the U.S. Army Advanced Construction Technology Center located in the Department of Civil Engineering, University of Illinois at Urbana-Champaign. The digital image and data-acquisition system hardware consisted of the following: (1) A PC equipped with Video Graphics Array (VGA) monitor and an EPIX, Inc., frame grabber with 20 Mhz pixel clock and 1 MB of image memory. One or two Sony CCD-F55 video camcorders, with a focal plane measuring 16.9 mm along the diagonal and consisting of about 250,000 effective pixels. The cameras were equipped with a 8x powered zoom lens, with a focal length range between 8.5 and 68 mm. For this study, video images were acquired with the zoom lenses locked at fixed focal length settings of 10, 12, 16, 22.5, and 32 mm. The system was also supported with 12 serial input/output ports, a video monitor, a video graphic interface printer, and a dot matrix printer. With the exception of the frame grabber, the hardware configuration had

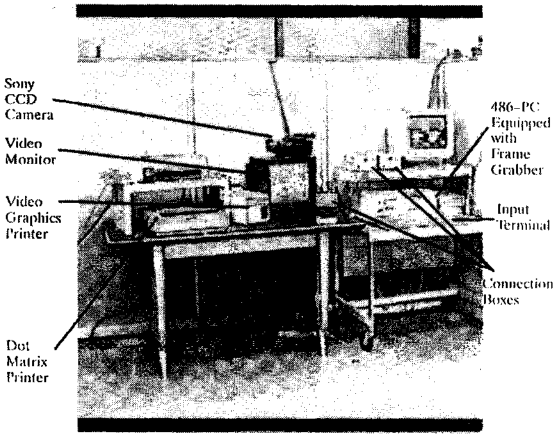

FIG. 1. Off-the-Shelf PC-Based Vision System Configuration

J. Surv. Eng. 1996.122:47-64.

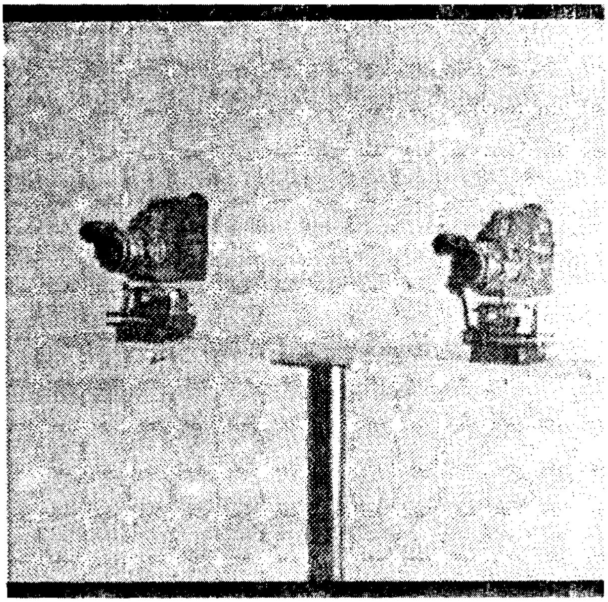

FIG. 2. Normal-Base Dual-Camera Setup

simple and low-cost components, which are becoming as common as household items. The primary function of this vision system in this research was limited to image capture and analog-to-digital (A/D) conversion. This was done to preclude results that were machine-dependent, and to give the user the flexibility to use an alternative image-capture device.

Camera Arrangement

The camcorders were used in two different arrangements to acquire stereo images of the mapped scene: normal-base dual camera and single camera. Fig. 2 shows the normal-base dual camera setup. The basic methodology of the dual-camera arrangement could be used in automatic mapping of the construction site and natural terrain by mounting the cameras on a tilting stage or a moving ground vehicle. This camera arrangement required that the cameras be calibrated for both the exterior and the interior orientation parameters. It is advantageous to use this arrangement in mapping areas that have no survey control because the fixed base provides the scale control. In contrast, its major drawbacks include camera movements after calibration and a small camera base. A single camera could acquire stereo images of a scene from two widely separated viewpoints, resulting in stronger geometry for the stereo intersection. The base/object distance ratio could be designed for better image geometry so that the entire imaging area of the focal plane can be utilized. Unlike in the dual arrangement, only the interior orientation parameters need to be calibrated. However, surveyed control points were needed.

Camera Calibration

The cameras were calibrated using a planar wall calibration method (Wong and Obaidat 1994). The program CCDCAL-PLANE was used for this task. The basic concept of this method is based on the condition that two bundles

J. Surv. Eng. 1996.122:47-64.

of rays from a stereo pair of images acquired by one camera for a planar object must intersect on the plane.

Actual Errors versus Statistical Analysis Scheme Errors

To evaluate the developed statistical analysis scheme, which is based on the error-propagation concept as the accuracy predictor for the extracted 3D measurements from stereo images, a set of convergent images were taken for different surveyed scenes from a construction site. Fig. 3 shows samples of stereo images of the two sites.

Different configurations of image scale, base/object distance ratios, and focal settings were studied to examine their effect on the accuracy of the 3D measurements. Table 1 shows the stereo image configuration for two sites used for this study using a single camera. A RMS residual error of image coordinates in the range of 0.07–0.24 pixels was obtained from the relative orientation process. Fig. 4 compares the estimated standard error with the actual error for different image scales. The pixel was selected as the linear unit of measurement for simplicity and generality. The results clearly showed that the vision system provided an accuracy of about one pixel (at the image scale) in extracting the 3D measurements for both the X and Z directions at both sites. Lower measurement accuracy in the range of four to five times the X and Z directions is expected in the Y direction because of the intersection geometry and the manual pointing to conjugate image coordinates. Estimated standard errors in the range of 0.2–1.0 pixels and 0.5–3.0 pixels were obtained from error propagation for the (X, Z) and Y directions, respectively. The 3D positioning accuracy was directly related to the size of the target as it appears in the image plane. The base/object distance ratio also has a significant effect on the accuracy of the measurements. The estimated standard errors for the 3D measurements may be considered realistic esti-

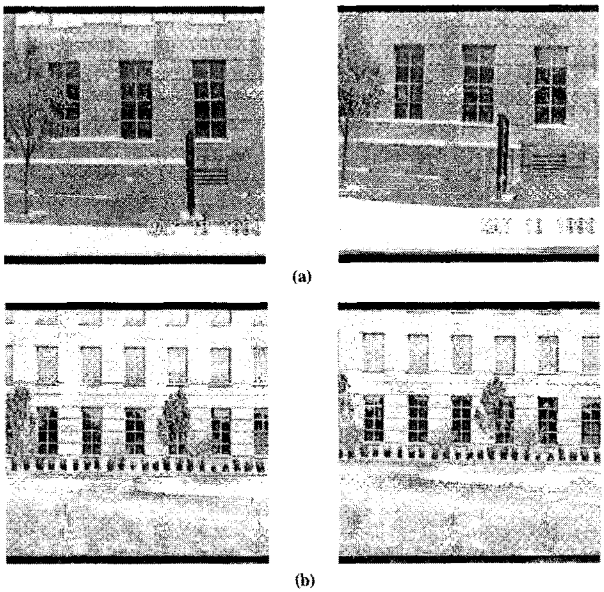

FIG. 3. Sample Stereo Images of Sites at Different Focal Lengths: (a) Site A ($f = 10$ mm); (b) Site B ($f = 16$ mm)

TABLE 1. Stereo Image Configuration and Scale for Different Focal Length Settings

Focal setting (mm) (1)	Focal length (pixels) (2)	Camera depth (m) (3)	Cameras' base (m) (4)	Base/object distance ratio (5)	Image scale (6)	Pixel size (cm) (7)
			(*a*) Site A			
10	950.9	18.420	1.340	1/13.7	1/970	1.94
12	1,111.7	18.420	1.340	1/13.7	1/830	1.66
16	1,502.7	23.900	1.420	1/16.8	1/800	1.59
32	2,989.9	53.000	12.50	1/4.24	1/890	1.77
			(*b*) Site B			
10	950.9	15.650	1.690	1/9.3	1/820	0.65
12	1,111.7	55.000	1.680	1/32.7	1/2470	4.95
16	1,502.7	55.000	1.680	1/32.7	1/1830	3.66
22.5	2,065.9	55.000	1.680	1/32.7	1/1330	2.66
32	2,989.9	63.500	1.220	1/52.1	1/1060	2.12

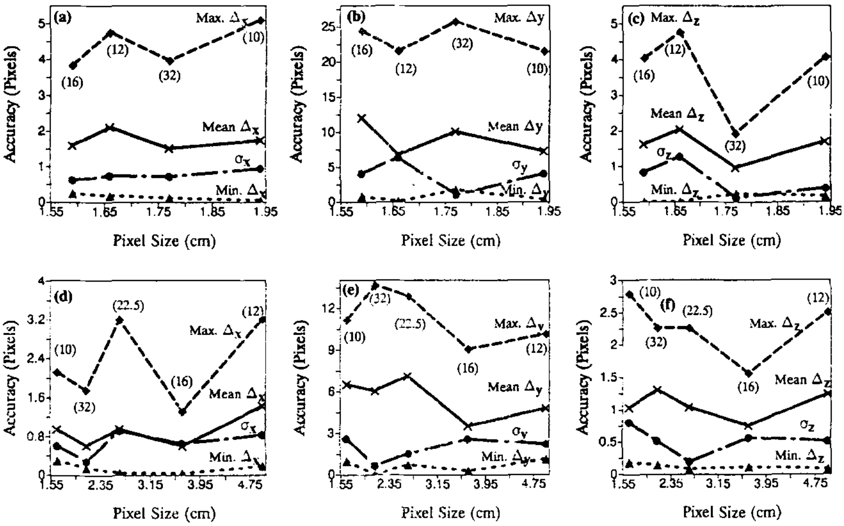

FIG. 4. Estimated Standard Errors (σ in pixels) of Statistical Analysis Scheme and Actual Measurement Errors (Δ in pixels)

mators for the accuracy of the measurements. Except for some cases in the Y direction, i.e., the depth direction, the actual errors were within three times the estimated σ values. Errors larger than 3σ were most often found to be caused by errors in the image matching of conjugate image points. This graphical representation is very important for three different reasons: (1) It gives the accuracy of the 3D measurements in pixels for different combinations of focal lengths and object distance; (2) it provides the focal length and the image scale for the given level of accuracy; and (3) it shows how realistic the statistical analysis scheme was in predicting the accuracy of the measurements. Thus, for any given camera configuration, the statistical knowl-

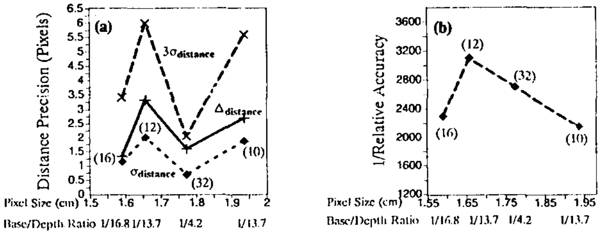

FIG. 5. Average Estimated Standard Errors and Actual Errors, and Relative Accuracies for Computed Distances (Number in Parentheses Are Focal Length Settings in mm)

edge-based approach could give the user an indication of the accuracy with which 3D surface measurements can be extracted during the planning stage. The results indicate that these data sets can be expanded to give an ample database consisting of focal length setting, camera configuration, image scale, and predicted 3D measurement accuracy. Consequently, the user can select the suitable camera configuration based on the required accuracy.

An average error of about two pixels (at the image scale) was obtained for the measured distances, while the estimated accuracy from the statistical analysis scheme was about one pixel. Fig. 5 shows the average estimated standard errors and the relative accuracy for computed distances at different image scales and base/object distance ratios. The relative accuracy consistently ranged between 1:2, 150 and 1:3, 100. The effect of the intersection geometry and the stereo image configuration is clear in the case of the 32-mm focal length setting. The relative accuracy is also worse for the small base/object distance ratio cases. This is obvious for the focal setting of 16 mm. Better accuracy was obtained when a larger base/object distance ratio was used. This was consistent with the results of another study based on laboratory 3D calibration yielding relative accuracies in the range of 1:1, 800–1:4, 500 for larger image scales (Wiley 1991).

The effect of the human operator errors on the measurement accuracy when fixing the base/object ratio for focal length settings of 12, 16, and 22.5 mm is shown in Fig. 4. The results show there is randomness in the measurement accuracy. Randomness is most likely due to image contrast and to human operator error during selection of conjugate image coordinates. The statistical analysis scheme can help detect these errors by predicting high estimated standard error values.

The effect of the number and distribution of the control points on the accuracy of the measurements was studied using five different control cases. Four control types were used, including (X, Y, Z) points, distance, difference in elevations, and vertical lines. The control was evenly distributed over the site. Better accuracy is obtained as the number of control points was increased and the distance between the control and the measured point was decreased. Of course, image contrast and sharpness of the edge to be measured are also important factors affecting the accuracy of measurements. Fig. 6 depicts the effect of increasing the amount of control on the 3D measurement accuracy and the coefficient of variation. Better accuracy, i.e., small coefficient of variation, is obtained as the number of control points is increased. The study showed the potential of developing a control scheme to be used in metric measurements. The scheme was based on an a priori absolute error value decided by the user. Then a sufficient number of control points could be selected in order to map scenes with the required accuracy.

J. Surv. Eng. 1996.122:47-64.

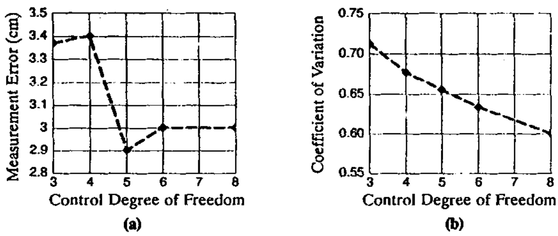

FIG. 6. Control Effect on 3D Measurement Accuracy

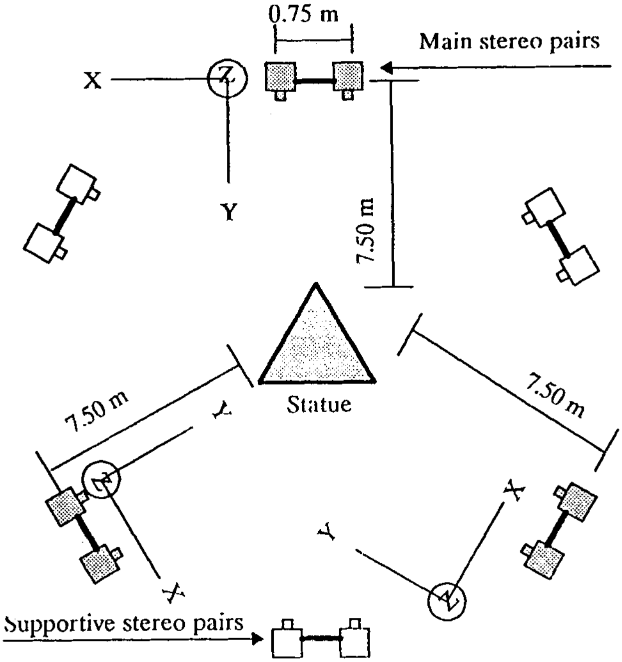

FIG. 7. Stereo Cameras Setup Used to Map Statue

Accuracy Level for Surface Measurement

Performing frequent calibration of the geometric distortion characteristics of the vision system is the key requirement to computer vision metrology. Therefore, the more stable the interior geometry of the CCD camera, the better the accuracy of extracting the 3D measurements.

Experimental results showed that the accuracy level of 3D measurements using the PC-based vision system was on the order of millimeters for both indoor and outdoor measurements. Relative accuracies of about 1/400–1/7,000 of the distance between the object and camera were achieved. In general, accuracy is improved by moving the camera closer to the object and increasing the camera base for stronger intersection geometry, i.e., using convergent photography. Therefore, a larger image scale is obtained. One drawback of this procedure is that it narrows the field of view of the camera. Accuracy also depends on the ability of the operator to position the cursor on the desired image point, which depends on the image contrast. Moreover,

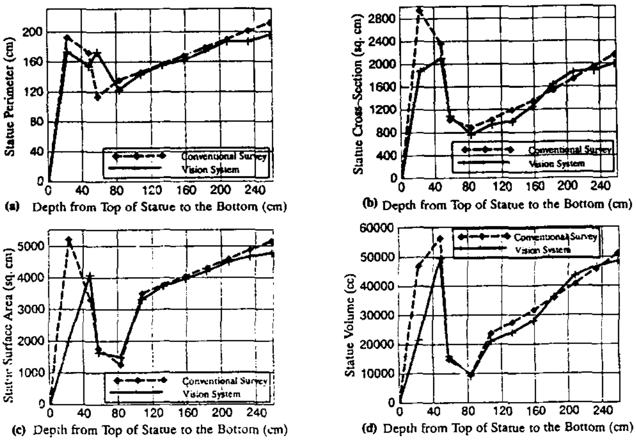

FIG. 8. Computed Perimeter, Cross Section, Surface Area, and Volume as Function of Depth of Statue for Both PC-Based Vision System and Conventional Survey

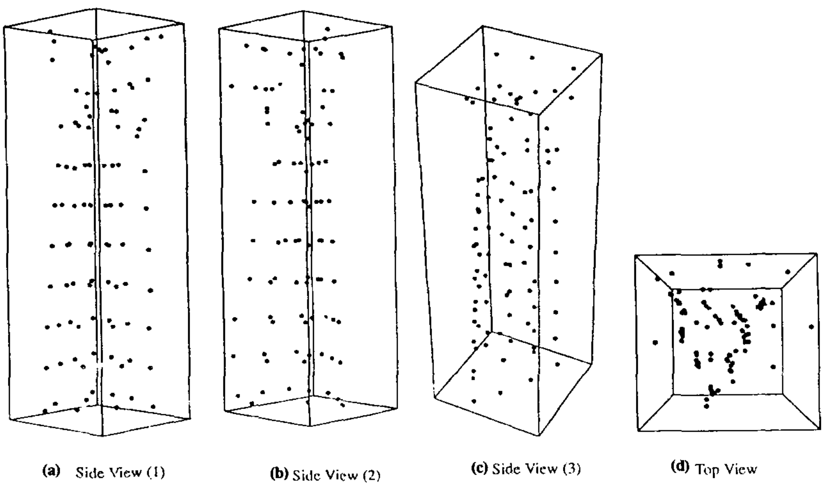

FIG. 9. Different Views of Statue Using 3D Measurements from Vision System

the number and distribution of control points directly affect the 3D measurement accuracy. Nevertheless, extracting 3D measurements with the aforementioned relative accuracy is promising, especially if compared with conventional survey methods such as stadia, which provides a relative accuracy of about 1/500 (Schmidt and Wong 1985).

A statue and a facade of the terrain area were mapped to study the potential of CCD cameras in extracting 3D surface measurements and topographic mapping. For this experiment, the zoom lens was locked at a focal length setting of 10 mm to obtain a maximum field of view. The limitation of the field of view of available CCD cameras made it difficult to map the entire area of each of the two scenes, to a specific accuracy requirement, in a single

J. Surv. Eng. 1996.122:47-64.

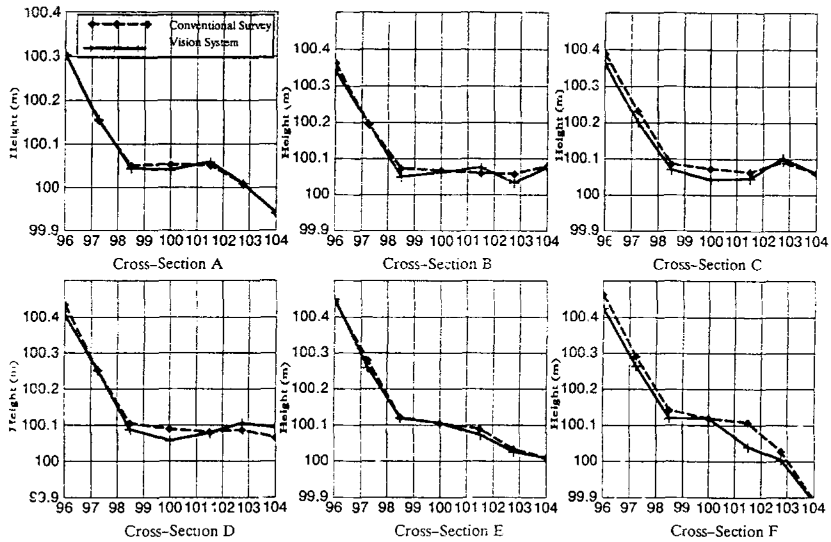

FIG. 10. Terrain Cross-Section Sketches in XZ Plane Using Measurements of Both Conventional Survey and PC-Based Vision System (Scale Is Different between X and Z Axis)

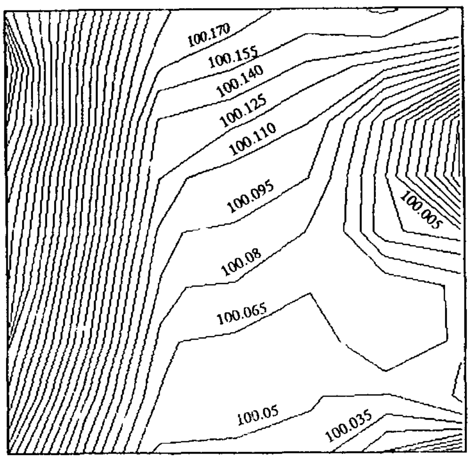

FIG. 11. Contour Plot for Mapped Terrain Area Using 3D Results from PC-based Vision System (Units Are in m)

stereo model. A multimodel approach was used to map both the scenes by using the dual camera setup. Six and four pairs of stereo images were taken for the statue and the terrain area, respectively. In both cases background contrast was the major problem. Therefore, pixel size tie points with colors different from the background were used as targets. Another function of these targets was to join the adjacent model segments into a single-model reference coordinate system, i.e., model linking. Fig. 7 shows the camera configuration used to map the statue.

J. Surv. Eng. 1996.122:47-64.

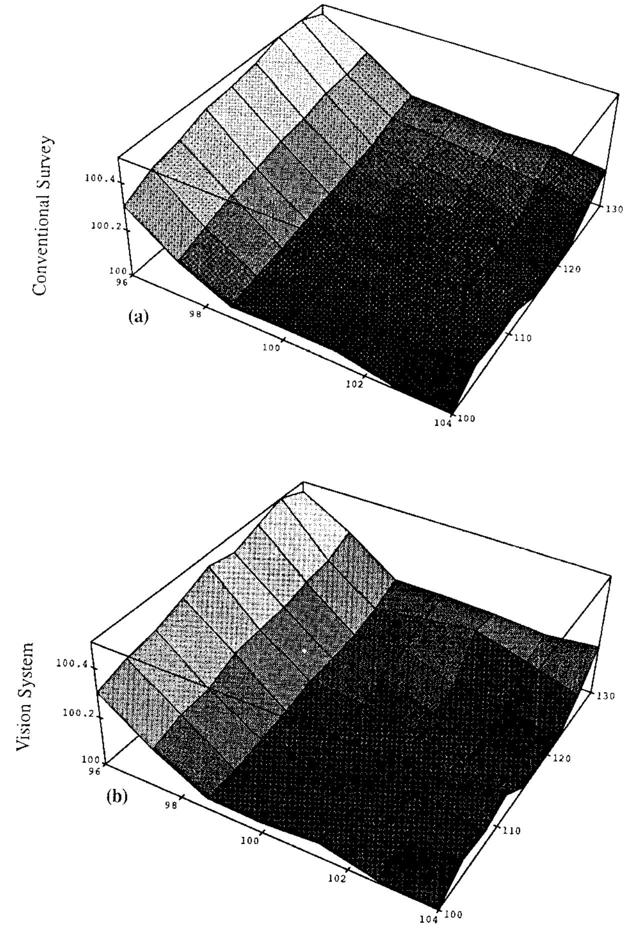

FIG. 12. 3D Digital Model for Mapped Terrain Obtained from: (a) Conventional Survey; (b) Vision System (Units Are in m)

Cross sections, perimeters, surface areas, and volumes were computed for the statue as a function of the statue depth. Fig. 8 shows a comparison between the results obtained from the PC-based vision system and the conventional survey. Except in an area of the statue that was affected by the contrast problem, i.e., the globe area, the accuracy of the results was consistent with conventional measurement approaches for all cross sections. The upper part of the statue contributed to a large percentage of measurement differences. The cumulative surface area and volume were within 8.2% and 10.4%, respectively. For the lower part of the statue, which had the tie points (i.e., excluding the globe), the accuracy of both surface area and volume was within 3%. Fig. 9 shows different views for the 3D digital model of the statue using the PC-based vision system 3D measurements. Limitations in the number of digitized image points affect the general representation of the digital model.

For terrain mapping, the PC-based vision system achieved an average error of about one pixel in the image plane for elevation. A graphical representation of the first six generated cross sections is shown in Fig. 10. Once the 3D coordinates were computed, a contour plot was generated (Fig. 11). Even reconstruction of the 3D digital mode is possible. Fig. 12 shows the 3D digital model generated from both the conventional survey and the PC-based vision system. A slight difference is found in the edge areas. This is probably due to errors extracting the conjugate image points and the aforementioned contrast problem. Nevertheless, mapping of a natural terrain area with a one-pixel accuracy capability is a promising aspect of CCD cameras.

CONCLUDING REMARKS

For close-range applications, knowledge-based systems, implemented using the basic photogrammetric rules and facts, could achieve surface measurements and mapping accuracy comparable to those of conventional field survey procedures. The results of this investigation indicated that the use of low-cost stereometric PC-based vision systems has potential in extracting surface measurements.

Actual errors for planar measurement were within one pixel, while errors were 4–5 pixels for the depth direction. Experimental results showed that the calculated errors from error propagation consistently fell within three times the estimated standard errors. Thus, the statistical analysis scheme using random errors in image measurement is proven to be a realistic estimator for 3D measurement accuracy. Test results showed that, with proper calibration, measurement accuracy of about ± 1(RMS) pixel in the image plane could be achieved consistently.

Study of different focal length settings and image scales gave significant results for the 3D measurement planning stage. The CCD camera user could determine an approximate accuracy for 3D measurements (at image scale, i.e., pixels) for different combinations of focal settings and camera configurations. This is extremely useful in the planning stage of photogrammetric measurement.

The study showed that requiring the human operator to perform the recognition task has the potential to bypass the technological bottleneck in automatic mensuration, recognition, and real-time measurement.

The results of this research showed that there is considerable potential for the use of PC-based vision systems in metrology applications. This potential can be most fully exploited if further research is directed toward the following tasks: (1) Automation of the image-matching procedures; (2) expansion and improvement of the effectiveness of the expert system; (3) development of design guidelines relating measurement accuracy to camera configurations, camera type, image scale, and focal lengths; (4) automation of the image recognition task through artificial intelligence techniques; and (5) investigation of lighting effects on 3D measurements.

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APPENDIX I.

A simplified mathematical model for the projective transformation equations between image and object-space coordinates systems is represented by the following:

$$X_j - X_i^c = \lambda_{ij}[m_{11}(x_{ij} - x_p + \Delta x_{ij}) + m_{21}(y_{ij} - y_p + \Delta y_{ij}) + m_{31}(-f)] \quad (1)$$

$$Y_j - Y_i^c = \lambda_{ij}[m_{12}(x_{ij} - x_p + \Delta x_{ij}) + m_{22}(y_{ij} - y_p + \Delta y_{ij}) + m_{32}(-f)] \quad (2)$$

$$Z_j - Z_i^c = \lambda_{ij}[m_{13}(x_{ij} - x_p + \Delta x_{ij}) + m_{23}(y_{ij} - y_p + \Delta y_{ij}) + m_{33}(-f)] \quad (3)$$

where

$$\Delta x_{ij} = \bar{x}_{ij}(l_1 r_{ij}^2 + l_2 r_{ij}^4 + l_3 r_{ij}^6 + \cdots) + [p_1(r_{ij}^2 + 2\bar{x}_{ij}^2) + 2p_2\bar{x}_{ij}\bar{y}_{ij}](1 + p_3 r_{ij}^2) \quad (4)$$

$$\Delta y_{ij} = \bar{y}_{ij}(l_1 r_{ij}^2 + l_2 r_{ij}^4 + l_3 r_{ij}^6 + \cdots) + [p_2(r_{ij}^2 + 2\bar{y}_{ij}^2) + 2p_1\bar{x}_{ij}\bar{y}_{ij}](1 + p_3 r_{ij}^2) \quad (5)$$

$$\bar{x}_{ij} = (x_{ij} - x_p)(1 + k);\ \bar{y}_{ij} = (y_{ij} - y_p);\ r_{ij} = \sqrt{(\bar{x}_{ij}^2 + \bar{y}_{ij}^2)} \quad (6\text{–}8)$$

where f = focal length; k = affine scale parameter; $l_1, l_2, l_3, \ldots$ = parameters of radial lens distortions; $m_{ij}(i = 1, 2, 3; j = 1, 2, 3)$ = functions of rotation parameters ω, ϕ, κ around image axes; $p_1, p_2, p_3, \ldots$ = parameters of asymmetric distortions; X_j, Y_j, Z_j = object space coordinates of object point j; X_i^c, Y_i^c, Z_i^c = object space coordinates of the exposure center c of photo i; (x_{ij}, y_{ij}) and $(\Delta x_{ij}, \Delta y_{ij})$ = image point j on photograph number i and its geometric corrections; x_p, y_p = image coordinates of the principal point; and λ_{ij} = photo scale factor at the image point j on photo i.

APPENDIX II. REFERENCES

Bouazza, A. (1992). "The use of the stereo photogrammetry method in geotechnical engineering work." *Proc., 29th Int. Congr. of Photogrammetry and Remote Sensing, Commission V*, Int. Archives of Photogrammetry and Remote Sensing, *Int. Soc. of Photogrammetry and Remote Sensing (ISPRS)*, Washington, D.C., 160–164.

El-Hakim, S. F. (1989). "A hierarchical approach to stereo vision." *Photogrammetric Engrg. and Remote Sensing (PE&RS)*, 55(4), 443–448.

Ho, W.-H. (1984). "The potential of a low resolution digital camera in close-range photogrammetry," PhD dissertation, Univ. of Illinois at Urbana-Champaign, Urbana, Ill.

Jansa, J., and Trinder, J. C. (1992). "A knowledge based system for close range digital photogrammetry." Int. Soc. of Photogrammetry and Remote Sensing, *Proc., 29th Int. Congr. of Photogrammetry and Remote Sensing, Commision V*, Int. Archives of Photogrammetry and Remote Sensing (ISPRS), Washington, D.C., 461–463.

Kretsch, J. F. (1988). "Applications of artificial intelligence to digital photogrammetry," PhD thesis, Purdue Univ., West Lafayette, Ind.

Miloshev, S. (1992). "Photogrammetric measurement of deformations." *Proc., 29th Int. Congr. of Photogrammetry and Remote Sensing, Commission V*, Int. Archives of Photogrammetry and Remote Sensing, Int. Soc. of Photogrammetry and Remote Sensing (ISPRS), Washington, D.C., 165–167.

Obaidat, M. T. M. (1994). "Video metrology for documentation of engineering construction," PhD dissertation, Univ. of Illinois at Urbana-Champaign, Urbana, Ill.

Sarjakoski, T. (1988). "Artificial intelligence in photogrammetry." *Photogrammetria*, Vol. 42, 245–270.

Schmidt, M. O., and Wong, K. W. (1985). *Fundamentals of surveying*, 3rd Ed., PWS-KENT Publishing Co., Boston, Mass.

Schneider, C.-T., and Sinnereich, K. (1992). "Optical 3-D measurement system for quality control in industry." *Proc., 29th Int. Congr. of Photogrammetry and Remote Sensing, Commission V, Int. Archives of Photogrammetry and Remote Sensing*, Int. Soc. of Photogrammetry and Remote Sensing (ISPRS), Washington, D.C., 56–59.

Wiley, A. G. (1991). "Metric aspect of zoom vision," PhD dissertation, Univ. of Illinois at Urbana-Champaign, Urbana, Ill.
Wong, K. W., and Obaidat, M. T. M. (1992). "DRSTEREO-a stereo measurement system for the PC." *Proc., Tech. Papers of the ASPRS/ACSM/RT 92 Meeting*, Am. Soc. for Photogrammetry and Remote Sensing (ASPRS) and Am. Congr. for Surv. and Mapping (ACSM), Md., 228–234.
Wong, K. W., and Obaidat, M. T. M. (1994). "CCD camera calibration using planar constraint." *Proc., Commission V Symp.: Close Range Techniques and Machine Vision, Int. Archives of Photogrammetry and Remote Sensing*, Int. Soc. of Photogrammetry and Remote Sensing (ISPRS), Washington, D.C., Vol. xxx, Part 5, 447–451.

J. Surv. Eng. 1996.122:47-64.