AUTOMATED 3-D MEASUREMENT USING MULTIPLE CCD CAMERA VIEWS

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Abstract

The goal of automated 3-D measurement of arbitrary objects using photogrammetric methods is a long way from being achieved, but significant progress is being made. However, automated measurement of small objects using inexpensive CCD cameras and frame grabbers is becoming increasingly common. A number of such systems have been developed both for commercial use and for academic research. It is within this latter context that a system to measure objects within a controlled environment has been developed at City University. The objective of the research is not only to produce a flexible measuring system for use in on-line inspection but also to address many of the fundamental problems that hinder 3-D measurement outside a controlled environment.

1. Introduction.

The development of fully automated photogrammetric measurement has been a possibility from the advent of electronic camera sensors together with the direct input of image information into computers. However, while it is relatively simple to recognise and locate automatically signalised target images, the complexity of the photogrammetric measurement method and the comparative lack of computing power have meant that it is only in the last few years that automated systems have begun to be developed. One area that would benefit from the development of automated systems is industrial inspection. It is generally recognised that inspection is an activity which consumes considerable resources, so both need and financial incentives for automation appear to exist. In this context the term *real-time* as defined by El Hakim (1986) as: *"a system without interruptions, or appreciable time lags, between acquiring the image and the final results that are the three dimensional co-ordinates"* could also be used instead of the term *automated*. A description of early work in this area may be found in a paper by El Hakim (1986), further developments have been described by: Fraser (1988); Gruen (1989); Wong (1992); Gruen (1992); Axelsson (1992); and Gruen (1994). The work of some representative researchers who have contributed to this field is illustrated in Table 1.

Table 1. A summary of some of the research in the area of automated 3-D measurement. (Least squares matching (LSM); Multi-photo geometrically constrained matching (MPGCM))

Author date	Ca	Application	Object size max./m³	Target	Feature location	Real time	Computing hardware	Features
El Hakim (1986)	2	Research	0.3	Bl. on wh.	Centroid	Yes	68010µP	Hardware
Haggrén (1987)	4	Inspection	25	Bl. on wh.	Centroid	Part	80286/80287	Sync. image acq.
Yamashita & Saiki (1988)	3	Human body	2	Laser	Peak	Part	Hardware	Line scan sensor
Jeschke (1990)	2	Geology	0.3	Nat. features	LSM	No	PC/VAX 11/750	Image pyramid
El Hakim (1990)	1	Inspection	0.5	Edges/proj	LSM	Yes	SUN 4/160	Table rotation
Beyer (1992)	3	Car body	5	Bl. on wh.	LSM	No	Sparc	Rotating object
Wong et al. (1992)	3x3	Human body	2	Projected	-	No	PC+Worksation	3-D control field
Maas (1992a)	4	Various	0.5	Projected	LSM	Part	-	High target density
Godding & Luhmann (1992)	3+3	Metrology	2	Retro	Ellipse	Part	Sparc 2	RSC cameras
Peipe et al. (1993)	1	Conveyor belt	1.2	Retro	LSM	No	80486	-
Aliverti (1993)	4	Human body	0.6	Laser	X correl.	-	SG 4D/25 Iris	≈50 pts./sec.
van der Vlugt & Rüther (1994)	1	Inspection	0.5	Projected	MPGCM	Yes	PC	Use of MPGC

It is worth noting that over many years the developments in the area of automated visual inspection have far exceeded those of automated 3-D measurement (Bayro-Corrochano, 1993a, 1993b). However, there is a trend towards the use of 3-D information. Photogrammetric methods would appear to be well placed to capitalise on this if off-the-shelf low-cost solutions can be developed.

Techniques that have been developed to enable automated measurement include: the use of object movement with a single camera; the use of multiple camera systems with a stationary object; set-up routines for initial camera orientations; the use of projection systems to signalise the object; area patch matching using least squares; and edge detection methods with controlled lighting. The salient features of automated systems are becoming clear, but there is still potential for further work in this area, especially in the development of cheap inspection systems for industry and the adaptation of the methods used in controlled environments for general use. As part of a programme of research in this area a measuring system has been constructed (Clarke & Robson, 1993) at City University to provide a research facility. The main features of the measuring system are: six CCD cameras with programmable exposure time linked to a single frame grabber; laser and projected light targeting; and facilities for controlling the environment such as lighting, projection systems, and rotation tables. This paper describes components of the measuring system and reports on some of the methods which have been developed such as automatic determination of the cameras' internal and external orientation parameters, and a method of solving the correspondence problem.

2. An overview of the measuring system components.

The development of an automated measuring system inevitably leads to the use of specific hardware to perform tasks under computer control. A specification of the likely tasks to be performed by a flexible measuring system resulted in the design and assembly of the following system illustrated in Fig. 1, the component parts of which are now described.

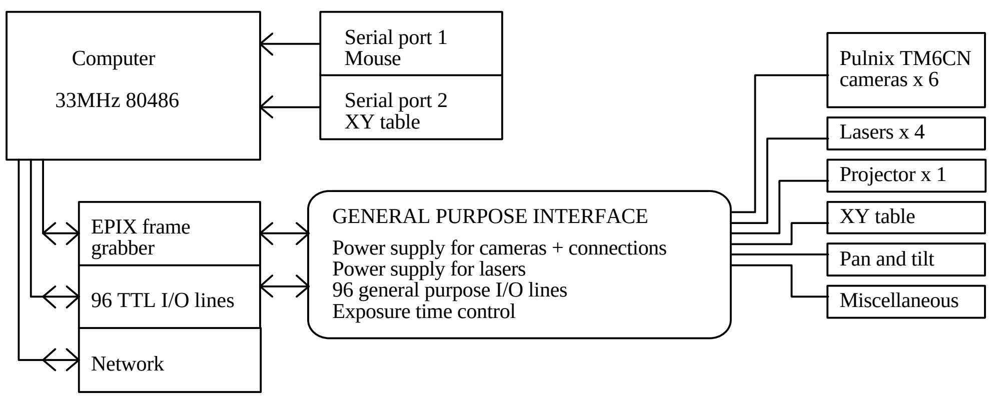

Fig. 1. Components of the 3-D measuring system.

The general purpose interface was designed and built to connect the computer with the measuring rig (Fig. 2). The objective was to allow the possibility of controlling all aspects of the measuring system such as: camera exposure time; switching of direct, diffuse, or camera axial lighting; projection of white light targets; switching of individual laser targets; object movement such as translations and rotations; and movement of the cameras to observe the object or target test fields for calibration purposes.

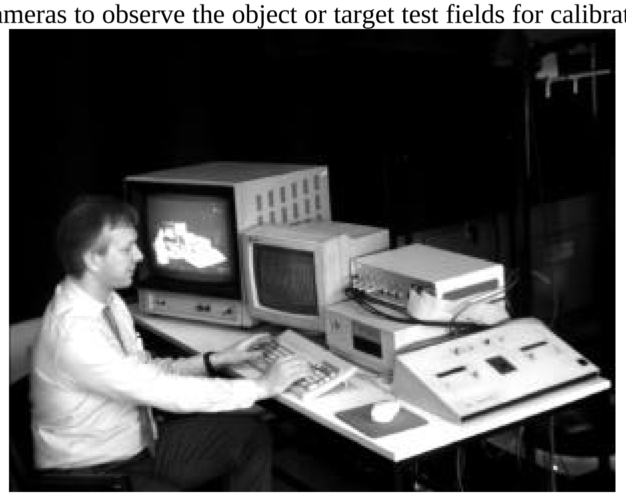

Fig. 2. The 3-D measuring system.

2.1 Computer. The choice of computer was based on two criteria: cost and functionality. A 486 PC is a suitable choice but the architecture of the IBM PC is a restriction on the speed of measurement and ease of programming. However, as a development platform it provides a reliable basis for interfacing, while mathematically intensive tasks can easily be performed over the network on a powerful workstation.

2.2 Parallel interface. A parallel interface (Computer Boards Inc., 1990) allows independent selection of ninety six output connections which can be set to a digital one or zero. These input-output (IO) lines are connected to the interface box and allocated to various tasks. In most cases these lines are used for output, but they can also be used for input, thus providing flexibility. Programming of the individual lines is simple but has some minor restrictions due to the chip architecture of the interface.

2.3 Camera exposure time. The Pulnix TM6CN CCD cameras (Pulnix, 1991) have the facility of exposure time control. This is essential in a system where adjustment of the aperture of the lenses is inconvenient and undesirable. Three pins within a separate electrical connector on the back of the camera are used to change the exposure time (Table 2). Each camera is connected to the parallel IO board. The control of the exposure time has been found to be flexible enough to cope with an average laboratory illuminated scene and that of a highly intense laser spot.

Table 2. Camera exposure time control selection options.

Pin 1	Pin 2	Pin 3	Shutter speed / sec
0	0	0	1/60
1	0	0	1/125
0	1	0	1/250
1	1	0	1/500
0	0	1	1/1000
1	0	1	1/2000
0	1	1	1/4000
1	1	1	1/10000

2.4 Camera pan and tilt. A further refinement in the use of the cameras is the individual orientation of the camera by the use of a pan and tilt mechanism. The camera is mounted in a small cage with the front node of the lens mounted at the intersection point of the pan and tilt axes (Fig. 3). Two rotational degrees of freedom are sufficient to locate the object to be measured within the field of view, but a design to rotate the camera by 90º about its axis is planned. The control of the two pan and tilt mechanisms is achieved using a stepper motor driver interface attached to a single nine pin connector (eight IO lines).

Fig. 3. The pan and tilt mechanism.

The advantages of controlling the orientation of all cameras are that objects which are too large for the field of view of a given lens can be measured and also each camera can be adjusted to view test fields such as a lens calibration frame. How useful this facility will prove in practice has yet to be established because only a single pan and tilt mechanism has been built for experimental purposes.

2.5 Lighting. It is useful to have diffuse and direct lighting available in the closed 3-D measuring environment. Diffuse lighting reduces the effect of shadows when using natural features. Direct lighting can be used for two purposes: to highlight edges; or to illuminate retro-reflective targets. Diffuse lighting is provided by illuminating white cloth with either fluorescent strip or spot lighting. Direct lighting is produced by circular ring lights around the camera lens for retro-reflective target illumination, or by individual lights placed to give high contrasting edges. Each light, whether powered by DC or AC, can be controlled by connection to one of the digital IO ports.

2.6 Targeting. The use of projected targets has to be considered in an automated system as a means of measuring what are often featureless surfaces. Although retro-reflective targets have ideal characteristics, the time required to fix them to the surface to be measured, and the relative sparseness of surface detail they provide make them less than ideal. Hence lasers and slide projectors will often be necessary. The use of lasers for targeting objects has often been limited to single point targeting. Furthermore, some lasers are inappropriate for use as high precision targets (Clarke & Katsimbris, 1994) and cost currently prohibits their use except for essential tasks such as camera orientation. A laser projection system (Fig. 4) is incorporated to provide four unique points for initial estimation of camera orientation parameters. These lasers can be translated along orthogonal axes by the operator. Projected targets are produced by a conventional slide projector with slides of different formats which are suitable for providing random or regular patterns on the surface to be measured.

Fig. 4. Diode laser collimator assemblies.

2.7 Object movement. Any form of object movement can be used with the system provided that it is connected to the digital interface. A stepper motor driven rotation table is currently being used for single camera experiments.

2.8 Software. Software has been written in C, and a simple DOS menu interface constructed to control the complete system. The objective is to provide a logical and easy to use system with step by step control of each element of the system to set up measurement. The interface could have been better written using the Microsoft Windows™ environment. However, no Windows driver was available for the frame grabber so this option has not yet been used.

3. Summary of the method of operation.

A number of automated, or semi-automated, systems have been reported by others (Table 1) so only those methods which are particular to this implementation or which have not been reported elsewhere by the authors are discussed in detail.

3.1 Initialisation.

Before measurement is possible the system must be initialised. This involves the mechanical adjustment of the cameras as well as the estimation of their orientation parameters.

3.1.1 Automatic estimation of camera position and orientation.

The automatic determination of camera exterior orientation is one of the first tasks which has to be solved in an automated 3-D measuring system. The emphasis of the research has been to develop a flexible system, so it has not been assumed that this information would be determined *a priori*, but that the cameras may be placed in any appropriate position and orientation. Two implementations of the closed form of space resection are examined. The first method uses a three line frame and the second makes use of laser diode collimators to project targets.

In a Cartesian co-ordinate system, the position and orientation of a camera are defined by six independent orientation parameters (three translational and three rotational). To determine automatically the parameters of transformation between the object co-ordinate system and the camera it is necessary to start by matching features observed in the image plane with corresponding features in object space. Given these correspondences, several commonly used techniques for solution of the camera orientation have been devised. The perspective transformation method of obtaining camera orientation has been widely used in computer vision especially for robot vision where subpixel precision is not necessary (Haralick, 1980; Haralick & Shapiro, 1993; Karara, 1979; Ayache, 1991). The Direct Linear Transformation (DLT) method (Karara, 1979) is widely used by the computer vision community for quickly acquiring transformations between image and object spaces. The geometric vector method, based on a closed form of space resection, derived by Fischler & Bolles (1981) provides a basis for an automatic camera orientation evaluation algorithm. This technique was improved by Zeng & Wang (1992) who produced a general solution of a closed form space resection for four co-planar object points. The vector calculation method can be divided into two steps: the calculation of the camera location parameters; and the calculation of the camera rotation parameters. The geometric vector method estimates the camera orientation parameters directly. No non-linear search or iteration is needed. Four co-planar object control targets provide a unique solution. For the method to work, the correspondence problem must be solved for each target image. Two methods have been used to locate and identify unique points: an automatic feature location method; and an automatic laser target location method.

3.1.1.1 Implementation by automatic line feature recognition.

An interactive method has traditionally been used to identify the correspondence between an object target and its image. If a fully automatic procedure to identify the correspondence is required, it is necessary to have unique features associated with each object target. In this implementation, a simple open rectangle made up of three coplanar lines provides a feature (Fig. 5) the orientation of which can be uniquely determined from any camera view using four points (two intersections and two terminations) provided that the feature is seen from one side only.

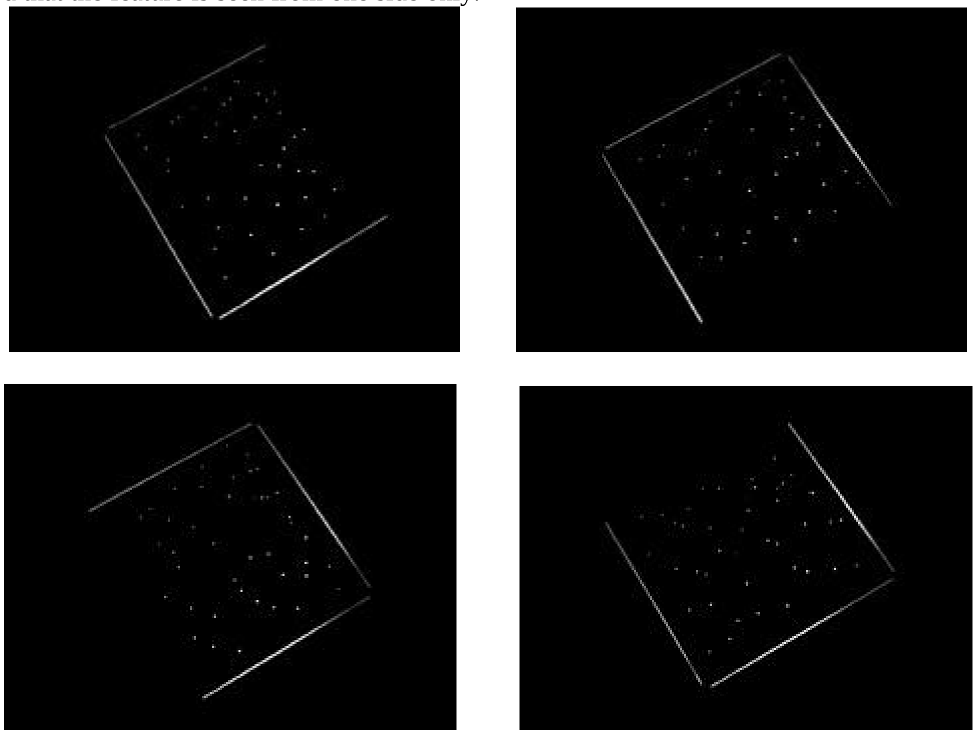

Fig. 5. Four views of the open rectangle.

If the 3-D co-ordinates of the four points at the ends of the lines are known, and the corresponding image co-ordinates are known, the camera orientation parameters can be estimated by the geometric vector method. The task of detecting and extracting the four image points and finding their corresponding object locations is now discussed. The sequence is as follows.

(a) Detection and extraction of line segments. The images of the rectangle sides are variable in width and so an extension of the Pavlidis thinning method (Pavlidis, 1982) is used, which is better suited to extraction of line segments.

(b) Merging of line segments. The thinned lines may be incomplete due to occlusions, so line segments in the images are merged after comparing the coefficients of the equations of the segments of the lines.

(c) Determination of the image co-ordinates of the intersection and termination points. The co-ordinates of the two intersection points between the two parallel rectangle sides and the third side can be calculated by solving two groups of equations for the co-ordinates of the intersection points labelled as 1' (x_1, y_1) and 2' (x_2, y_2). The co-ordinates of the two termination points are labelled as 0' (x_0, y_0) and 3' (x_3, y_3) respectively. Although at this stage four image points have been recognised and measured, their correspondences to the object targets must be decided as it is possible to match to object targets 0, 1, 2, 3 in order of 0', 1' 2', 3', or 3', 2', 1', 0'. Correct correspondence is achieved by the use of a right handed rule.

The four pairs of image co-ordinates are converted from pixel to millimetre units and the geometric vector method used to obtain estimates of the camera orientation parameters.

3.1.1.2 Implementation by automatic laser target extraction.

A disadvantage of the foregoing method is that it requires a special frame to be placed in the field of view of the cameras. An alternative method which uses diode laser collimators has also been developed. Four lasers are used to enable automatic estimation of approximate camera parameters. The configuration of the system is shown in Fig. 4. The lasers are arranged to be parallel to each other and are fixed to an aluminium plate with an array of holes so that the four lasers can be placed in different positions depending on the size and shape of the object to be measured. The aluminium plate is fixed to a translation table which is controlled by the computer through the parallel IO port. The correspondence between the laser spot in object space and the laser target images in the image plane is obtained by switching specific lasers on and off. To avoid unnecessary switching a method is adopted in which only two images are grabbed. First, one laser is switched on to obtain the correspondence of the laser spot and its image co-ordinates. Second, the remaining three lasers are switched on and the image co-ordinates of these three laser spots are captured. By analysing the image co-ordinates it is possible to identify uniquely each of the four target images. The known separation and parallel alignments of the lasers are with the geometric vector method used to estimate the camera orientation parameters.

3.1.2 Camera calibration.

Camera calibration should also be a part of an automated measuring system. Appropriate methods are required to provide calibration information, for example by the use of targets or linear test fields.

3.1.2.1 Calibration using a linear test field.

A method described by Fryer et al. (1994) and implemented at City University provides a mechanism for on-the-job calibration of CCD camera lenses of the type used in this measuring system. The method can be implemented in two ways, either by the use of a calibration frame that is separate from the object to be measured, or by surrounding the object with the calibration frame. In either case it was found that, for the lenses used, the estimates of the lens distortion parameters were not significantly different from values obtained from more rigorous methods. This technique does not provide an estimation of the principal distance, nor of the principal point offsets. However, other work reported by Robson et al. (1993) based on the work of Burner et al. (1990), has shown that the principal point offsets and their standard deviations can be determined for each camera relatively easily and used as *a priori* values in a subsequent bundle adjustment.

3.1.2.2 Test field calibration.

A common method of calibration for principal distance and principal point offset is to use the camera in a multi-station convergent configuration around a test field such as that in Fig. 6. This is not easy to implement when different cameras are used in a single convergent configuration around the object to be measured. It is possible to replace the object by a test field, but each camera will then produce only one view of that test field, so unreliable or inaccurate estimates of some or all of the inner orientation and lens distortion parameters will be obtained. The alternative is to estimate the interior orientation parameters for each camera independently first and then use these values with their standard deviations in the subsequent multi-camera measurement of the object or the test field. Although this procedure does not conform to the principle of full calibration at the time of measurement, it does give some check on whether or not the calibrated values have changed at the time the object is measured. Large corrections to the *a priori* values would indicate that some change may have taken place and that full re-calibration might be necessary.

Fig. 6. Target test field with open rectangle.

3.2 Target recognition, and subpixel target location.

Reliable recognition and subpixel location of target images are important first steps in the measurement process. The next step is to solve the correspondence problem for multi-camera measurement. This can be achieved by a technique using the epipolar line method if the targets cannot be uniquely identified in each image (Maas, 1992b), or recognisable features can be used (van den Heuvel, 1993). The latter method is seldom used because of its lack of flexibility, whereas the former method is not universally used because of the requirement for the camera's internal and external orientation parameters to be known. To overcome these problems a dual approach is used.

(a) Feature based matching, when known (or assumed) characteristics of targets in a binary image, such as area, perimeter, or degree of circularity are used followed by the computation of the location of the centroid of the target image.

(b) A correspondence algorithm is used with the bundle adjustment to solve gradually the correspondences between targets and at the same time refine the estimated camera parameters.

The procedures used for recognition and subpixel location of target images have been described elsewhere (West & Clarke, 1990; Chen & Clarke, 1992; Clarke et al., 1993). The correspondence algorithm described by Chen et al. (1993) is less well known and still under development and so is summarised here.

3.3 Solving the correspondence problem.

It is possible to solve the correspondence problem for control targets by the use of unambiguous features with rule based interpretation (Section 3.1), but it is not practicable to match in this way the large number of targets necessary for 3-D measurement. The traditional epipolar line method is based on the intersection of straight lines in image planes and can solve correspondences between targets. However, the epipolar line method has some limitations.

(a) Accurate camera orientation parameters are required otherwise errors are likely to occur in the epipolar line location resulting in correspondence mismatches.

(b) The epipolar line is modelled as a straight line, but the projected line will be distorted by the lens, and by other systematic effects in the system used.

(c) The value of an appropriate tolerance band depends on the accuracies of the camera orientation and the target image location and any chosen value which does not depend on these may not always be appropriate.

An alternative correspondence solving technique is described which uses initial approximate estimations of the camera orientations. The method, which is combined with a bundle adjustment process, is based on 3-D intersection and an epipolar plane, as opposed to the 2-D intersection in the epipolar line method.

3.3.1 The 3-D space intersection method.

The target image co-ordinates x_i and y_i are estimated by the centroid method. These measured image positions will contain errors arising from deviations from collinearity caused, for example, by lens distortion. Such discrepancies are usually modelled by careful use of additional parameters included within the functional model. If the model, the camera parameters, and the target image co-ordinates are without errors, rays projected from each target image will intersect at the object target in 3-D space. Under these conditions correspondences can be determined by locating intersecting rays. With the epipolar line method the intersection is performed in the image space, and ambiguities occur because different targets which lie along, or close to, a single ray are all candidates for matching. In practice the rays will not intersect in the object space because of errors in the estimated parameters, the model, and the target image co-ordinates. The correspondence method which is described here measures the shortest distance between projected rays and compares it with a tolerance to find candidates for target matching. The 3-D tolerance is equivalent to the 2-D tolerance used in the epipolar method. The method is illustrated in Fig. 7 by the use of two camera viewpoints where it can be seen that whilst the two rays do not intersect at a single point in space, the distance **D** can easily be calculated (Chen et al., 1993).

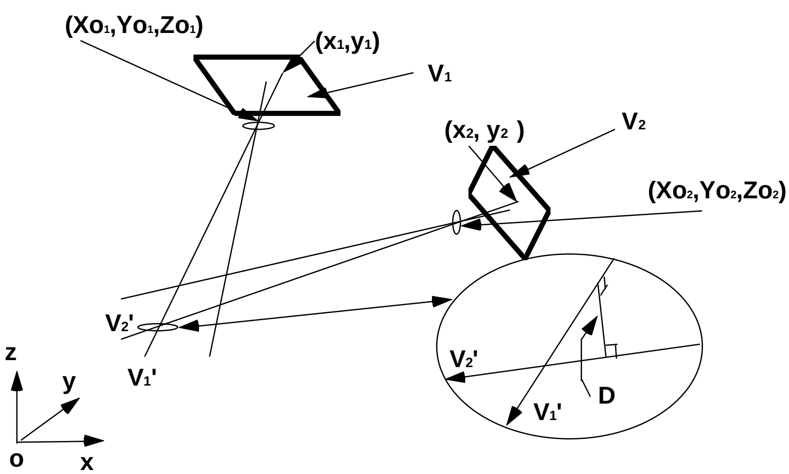

Fig. 7. The 3-D space intersection method.

There are two differences between this and the epipolar method.

(a) The epipolar line method performs the correspondence checking in 2-D while the 3-D space method does it in 3-D. The advantage is that the additional parameters used in the bundle adjustment are taken into account. By contrast the epipolar line method can compensate for lens distortion and other error sources, by correcting the original data or by using appropriately curved lines. However, this requires the predetermination of these additional parameters which is not always convenient.

(b) The threshold values for judging correspondences between image views are different. The 3-D space method uses the standard deviation of targets in 3-D space whilst the epipolar line method uses the residuals from the collinearity equations.

3.3.2. An iterative solution to the correspondence problem.

The usual use of the epipolar line method requires that the camera parameters are accurately defined. These parameters are difficult to evaluate in a working environment as they are usually obtained through a bundle adjustment which cannot occur until the correspondence problem has been solved. This problem with the epipolar method and poor knowledge of the network geometry can be overcome by combining the bundle adjustment with the target matching. One of the advantages of the bundle adjustment is that it iteratively evaluates the 3-D co-ordinates of targets to known precision and at the same time improves camera exterior orientation and lens distortion parameters. Because the correspondence matching method and the bundle adjustment are so closely related it is possible to perform both procedures at the same time. In the first iteration of the matching procedure, a few matched target images are determined using the initial approximations of the camera viewpoint parameters (section 3.1.1) and an initial 3-D tolerance. A bundle adjustment is then computed and the refined camera orientation parameters are fed back into the matching algorithm, with a new 3-D tolerance, and new targets are found. By these means the process is refined and repeated, the network strengthened, and all (or nearly all) target correspondences are found. While it is possible to do the same with the epipolar method, to the authors' knowledge this has not been reported. Hence, a method has been developed not only to solve the correspondence problem but also without the requirement of knowing precise camera parameters.

The 3-D tolerance distance defined by **D** is evaluated using the existing target standard deviation computed during the bundle adjustment. Hence, the tolerance is a function of the precision of the estimated 3-D co-ordinates at each iteration of the bundle adjustment. In the matching procedure, it is important to avoid errors due to target ambiguities and occlusions. Two stages (Chen et al., 1993) are used to improve reliability: a global uniqueness constraint which uses multiple-viewpoints to match all targets, except where an occlusion or ambiguity occurs (stage one) and; a local uniqueness constraint to overcome such problems by selecting a subset of the viewpoints (stage two). The two stage method, combined with a bundle adjustment procedure, makes the matching more robust by the gradual introduction of additional targets. Using multiple-viewpoint constraints for target correspondence improves the reliability of matching by only matching targets appearing on all viewpoints and rejecting all occluded and ambiguous targets. The iterative process allows the strengthened network to support the introduction of more targets into the matching procedure. Occlusions are overcome by adding more viewpoints. Ambiguities are solved by isolating the view on which more than one target has the same intersection.

4. Summary of the procedure.

(a) The camera orientation parameters are automatically estimated by either the open rectangle method (section 3.1.1.1) or the laser spot method (section 3.1.1.2) to give the starting values of the exterior orientation parameters for each camera.
(b) A target is selected in an arbitrarily chosen primary image and the tolerance computed for all of the targets in the remaining secondary images.
(c) The distance **D** for each ray from each secondary images considered with each ray from each primary target image is compared with the selected tolerance value. If any of the distances is less than the tolerance the relevant targets are noted as a possible match. If there is only a single value the corresponding target images are stored as a correct match.
(d) Procedures (b) and (c) are repeated for all targets within the arbitrarily chosen primary image.
(e) The (X,Y,Z) co-ordinates of targets whose images have been successfully matched are loaded into the bundle adjustment which is then recomputed. As the network gets stronger and the parameters are refined, the 3-D tolerance value is reduced and procedures (b)-(d) are repeated until all possible target correspondences are found and the solution has converged.
(f) An additional similar procedure is used to match the remaining target images to take into account targets which occur in a subset of the image set.

The benefits of the full 3-D method of correspondence solving combined with a bundle adjustment procedure are:

(a) initial camera parameters estimates are not required to a high accuracy;
(b) initial values are improved by bundle adjustment based procedures;
(c) target matching tolerances can be changed during the bundle adjustment process according to a derived statistics;

(d) targets can be progressively introduced into the measurement network enabling a more robust correspondence matching technique;
(e) the procedure is founded upon the current network precision.

While it is not claimed that this method is capable of improving the reliability of correspondence matching (further analysis and testing of the algorithm both by simulation and practical experiments is continuing) it is expected that this method may be equivalent to the epipolar method, and possibly superior in some respects. For many of the experiments conducted to date, the method has proved reliable. Procedures for optimising the method have also been studied and implemented.

5. Results.

The task of measuring objects placed within the measurement frame is gradually being refined and improved. At this stage, the process of measurement has been considerably simplified but flexibility has been retained. The orientation of the cameras is usually unknown prior to beginning the measuring process, and the cameras are not firmly fixed i.e. the orientation of the cameras is not assumed to remain precisely the same between measurements. The system has not yet been optimised either for speed or robustness. Individual components of the system are being developed and studied. Considerable scope exists for improvements.

To provide an illustration of the operations required to measure a very simple object, targets were placed on the surface of a large convex mirror (Fig. 8).

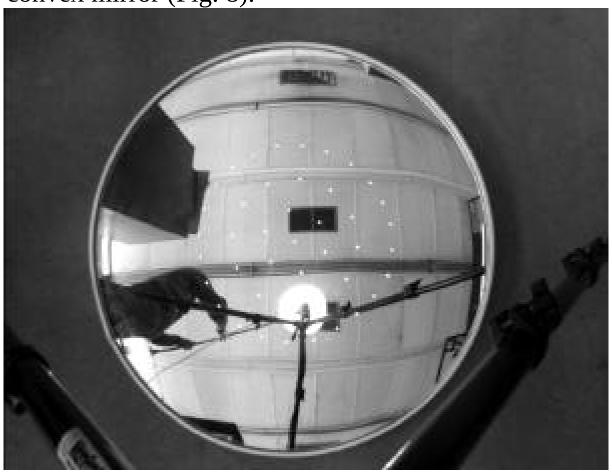

Fig. 8. Image of targeted mirror.

The mirror was measured using a single camera viewing the mirror from four positions with a ninety degree roll about its axis at each position resulting in eight images. The forty three targets provided 514 degrees of freedom in a free bundle adjustment. The results of the adjustment are given in Table 3.

Table 3. Results of a free bundle adjustment.

rms. image co-ordinate standard deviation		rms. object space standard deviation		
x/µm	y/µm	X/mm.	Y/mm.	Z/mm.
0.21	0.20	0.008	0.008	0.011

The image co-ordinate rms. values equate to approximately 1/40th of a pixel image resolution, and the rms. co-ordinate of a target corresponds to approximately one part in 30,000 of the 280 mm. sized object. Further work is required to compare such results with other methods, and it is hoped that a number of test objects can be obtained that have been measured by other measuring systems of a higher order of accuracy than is obtainable by the method described here.

6. Conclusions and further work.

This paper has described research work in progress at City University to develop an automated 3-D measuring system using multiple camera views. This work has been placed in context with other work in this area where it can be seen that although many systems contain an automated aspect, the number of fully automated measuring systems is still relatively small. However, demand for automated measurement is ever increasing, hence it is hoped that the work described here will contribute to the development of the long term goal of the automated measurement of arbitrary objects in a working environment. This paper has concentrated on aspects of work at City University that have not been widely published elsewhere whilst retaining an overview of the complete system. The main features have been: the interfacing system and components; the automatic estimation of camera parameters, an automatic solution to the correspondence problem, and the results of measuring a simple object. While many aspects have been dealt with, further work is required in areas such as: the use of multi-photo geometrically constrained matching; target densification; improving the speed of operation; alternative target projection methods; an analysis of accuracies and sources of systematic errors; and the presentation of the results in a useful form.

7. References.

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