LASER DOT MATRIX BASED DIGITAL SYSTEM FOR FOR MONITORING TEXTURELESS ROOF STRATA OF MINES

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ABSTRACT

Projection of a large number of target points through a tiny diffraction grating based diode laser is used to solve two close range digital photogrammetric problems: conjugate point identification and targetting the object. Laboratory investigations showed high spatial stability and repeatability of dot matrix projection through a diffraction grating. A measurement repeatability of around 1/30th of a pixel was achieved during their image co-ordinate measurement by least squares based template matching. Accurate calibration of the projector was done with the help of an autoreflecting spherical target and placing the projector rigidly over the telescope of a geodimeter. Using standard bundle adjustment procedures of photogrammetry, a camera model of the projector was developed. The interior orientation and lens distortion parameters of the projector were found comparable with those of a real CCD camera which were derived using a standard three dimensional testfield. A CCD camera placed over a motor driven turning and tilting system is combined with this arrangement of the projector to scan a large surface area and automatic derivation of three dimensional information of a textureless and featureless object can be achieved.

1 INTRODUCTION

Mining measurements and inspections are quite different from those of other industries due to both time and space constraints. These constraints force a measuring system to be remote, portable, fast, robust and accurate. Further, due to the inhomogeneous nature and anisotropic character of the rock mass, there is a requirement for continuous measurement in space. Both quantitative and qualitative (pictorial) information are equally important for analysis purposes because the relationship between stress and strain of the rock mass is not exactly known. CCD based digital systems have vast potential for such measurements and, recently, a number of attempts have been made to utilise such systems for underground inspection [Keran & Hendricks, 1995], measurement [Singh et al., 1991] and guidance of machines [Hurteau et al., 1991]. The work discussed here is aimed at the development of a suitable system to monitor the movement of massive sandstone strata during partial (Figure 1) extraction of coal under built-up surface structures. Here deformation monitoring of hanging structures involves extensive measurement of unapproachable areas to estimate the nature of stability of overlying strata.

1.1 Problem of massive sandstone strata

The monitoring of massive sandstone strata generally corresponds to remote measurement of a nearly flat, textureless and featureless surface (Figure 2). Due to the light weight and small size of CCD imaging systems, a conventional two camera system initially seemed to be feasible. However the requirement for synchronised photography (unstable object) and lack of features (for stereomatching) in the object space restrict its application to this problem. Other approaches like CCD based shadow profilometry [Maerz et al., 1990] face two serious problems: (1) inaccessible and dangerous areas of the mine can not be measured by this technique as a linear feature has to be placed over the object and (2) subpixel measurement of both X and Y co-ordinates of the image point is very difficult for a continuous linear feature like the shadow of a string. Projection of a laser line in the object space

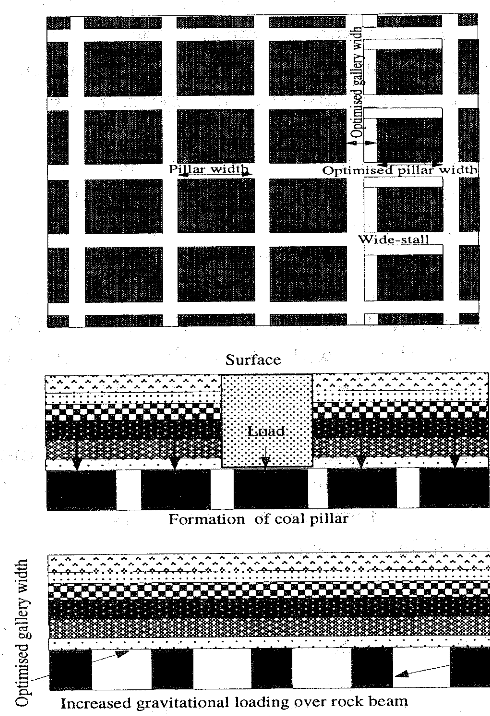

Figure 1: Intact roof with partial coal extraction (plan and sectional views).

provides a better solution for remote measurement in poor and controlled light conditions underground but the accuracy problem remain.

1.2 Laser dot matrix projection

A diffraction grating based dot matrix projector (Figure 3) is an attractive option not only due to its small size, light weight and simple mechanism but it provides an effective way to place a large number of high contrast measuring targets over the object. The known orientation of these laser dots

Figure 2: Cross section of deforming sandstone roof strata.

can be used during three dimensional measurement. Further this system of projection provides sufficient depth of field to accommodate the range variation during this measurement. The centroid of the large number of distinct targets (laser dots) can also be located precisely through different suitable algorithms and so the accuracy problem of line projection or shadow profilometry does not exist. The laser projector was

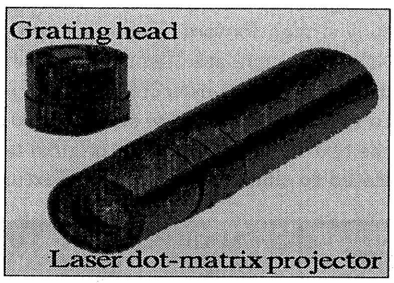

Figure 3: A laser dot matrix projector, overall 8 cm long and 1.7 cm of diameter.

rigidly attached with the telescope of a geodimeter (Figure 4) for accurate calibration of interdot angles among the laser dots and other measurement purposes.

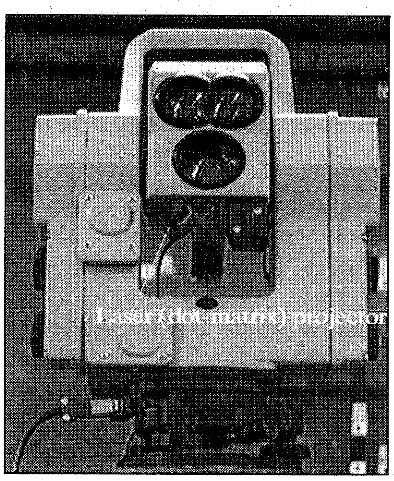

Figure 4: Placement of the laser dot matrix alongside the telescope of geodimeter.

1.3 Design constraints

A detailed consideration of the impact of the mining environment revealed that a CCD based system can be deployed for data acquisition during partial extraction of coal under massive sandstone strata. The design of a close range digital photogrammetric system for industrial measurements involves a number of factors including imaging geometry configuration, storage of digital data and field of view/resolution problems due to the small format of the commercially available CCDs. A detailed discussion about network configuration task is presented by Mason (1995). The analogue signal acquired during industrial measurement by a solid state camera creates large amounts of data and a host computer is required in the vicinity of the camera for frame-grabbing and storage. Although a number of alternatives like PCMCIA and DCS 420 (Kodak) cameras are coming up as a solution to this problem the readily available camcorder may also be considered as an intermediate data storage device in the industrial environment. Performance testing of a camcorder as a data storage device [Singh et al., 1995] provided subpixel image co-ordinate accuracy with the help of a suitable image co-ordinate measurement algorithm. The dot matrix projector fixed rigidly with the telescope of a geodimeter is combined with another arrangement (Figure 5) in which a CCD camera is placed over a motor driven turning and tilting system to overcome the field of view problem and automatic derivation of three dimensional information of the object space.

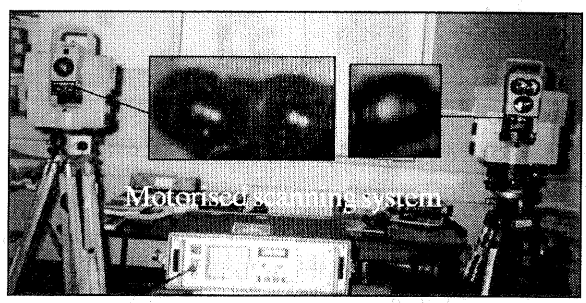

Figure 5: Turning and tilting based scanning system.

CCD based remote inspection and measurement have enormous scope in hazardous areas [Chapman et al., 1992] but the limitations of the stereomatching techniques during identification of corresponding points in stereopairs at close range provide a way for active triangulation techniques for such measurements. Light projections have been practiced a number of times for different automatic measurement purposes like robotic vision [El-Hakim, 1985] and measurement of dynamic textureless objects [Ethrog, 1991]. Unfortunately, these systems involve inconvenient calibration procedures for a photogrammetrist. Furthermore, until recently, no suitable projection method was available for remote placement of high density spatially stable measuring points. In this work the projector is treated as a virtual camera and a camera model for the projector is developed using bundle adjustment. Precise knowledge of the orientation parameters of the camera and the projector is used for three dimensional object space information by intersection of the known orientation of each dot of the projector and their respective measured image co-ordinates.

2 CENTROID LOCATION

To meet the level of accuracy of close range industrial surveying/inspection from low resolution images of a commercially available CCD camera, subpixel image co-ordinate measurement becomes important. Most widely used algorithms to measure centroid location of a target point are based on a thresholding technique. Targets placed over the object surface generally contain substantial difference in grey level value with the background so recognition and location of these targets in a digital image is done by setting a suitable threshold of grey level for the image. Disproportional influence of low intensity outer pixels on centre of mass calculation may be removed by weighting pixel position with the corresponding grey values of the pixels [Trinder, 1989]. This approach reduces the influence of incorrect thresholding but errors due to noise and uneven illumination become more significant. Attempts are also made by different researchers to recover perspective image distortion of circular targets by ellipse fitting, focal length normalisation and Gaussian shape fitting. However, the selection of a suitable threshold to segment the real target area in a digital image (Figure 6) remain a major problem for threshold based approaches.

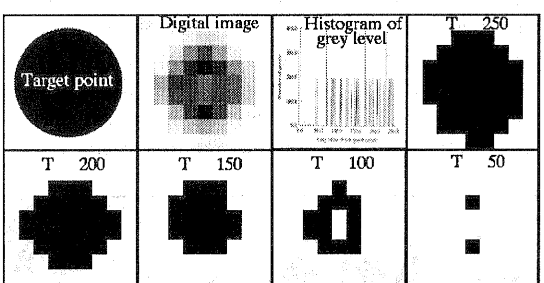

Figure 6: Asymmetry of a target image during different levels of thresholding.

Differential variation of contrast of the target points with that of the object's surface makes it very difficult to detect the correct boundary of a target point. There is a considerable influence of change in contrast and texture of object surface on the target image information (Figure 7). A textured object surface makes it very difficult to isolate the correct target area.

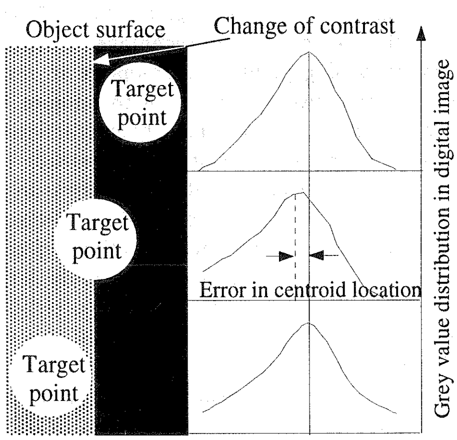

Figure 7: A simple case of texture influence on centroid location.

2.1 Template matching

In practice it is very difficult to obtain an object with uniform texture. Even the surface of a massive sandstone strata does not have ideally uniform texture. Beyer's (1992) investigations for precise digital measurement found least squares based template matching to be the best solution for subpixel target location of a well targetted textured images. A comparison of simulation results for centroid location by different techniques [Trinder et al., 1995] show best performance of a least squares based template matching for flat targets. Gruen's (1985) "adaptive least squares correlation" algorithm was modified at UCL [Otto & Chau, 1989] to a "region-growing" algorithm which provided excellent performance for automatic three dimensional measurement [Day & Muller 1989] from low resolution aerial and satellite images. The basic adaptive least squares correlation algorithm has vast potential for accurate centroid location and was used during this study.

2.2 Template selection

In least squares based template matching, the algorithm finds the best match of grey values for a patch called a template to a patch around the estimated point in the image allowing affine transformation. Best match minimises the sum of the squares of the grey-level differences between the two patches. As discussed above, least squares template matching performs well for centroid location of target points placed over a textured object but the selection of a suitable template is not completely straightforward. There are two possibilities for template selection: simulated templates of different symmetrical nature and templates extracted from the image itself. It is possible to simulate templates of different texture characteristics but the texture variation of the original target image is too complicated to simulate (Figure 8). Texture variation

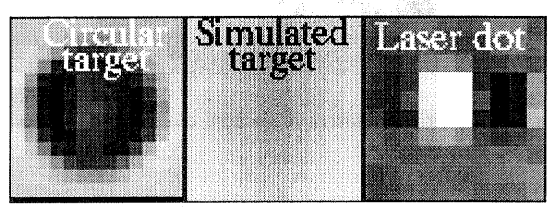

Figure 8: Texture variation in different templates.

is the most important factor for the accuracy of least squares based template matching. For both active and passive targets (Figure 9) simulated templates provided poorer results in comparison to those of the templates extracted from the image. For symmetrical target points, such as those produced by the diffraction grating based laser diode, the template extracted from the image itself provided the best results.

2.3 Optimum size of template

The adaptive least squares matching algorithm uses an iterative "linearise and solve" strategy. It is only likely to converge if the initial estimates are good, so the nature and size of the template play an important role during matching. Particularly for a template extracted from an image, the size of the template is an important factor. It is difficult to provide a figure for the dimension of the template for different measurements but minimum number of iterations and low eigen value criteria can easily provide the optimum size of template for a particular measurement. Different measurements were made by varying the dimension of the template to find the optimum size of the template. The variation of number of iterations and eigen values of the covariance matrix for different template size is shown in Figure 10 and Figure 11 respectively. From these measurements it was observed that a template of around 1.3 times the size of the target image provides optimum performance. A simple statistical analysis of repeatability of image co-ordinate measurement of these targets in different frames is shown in Table 1. The accuracy of this

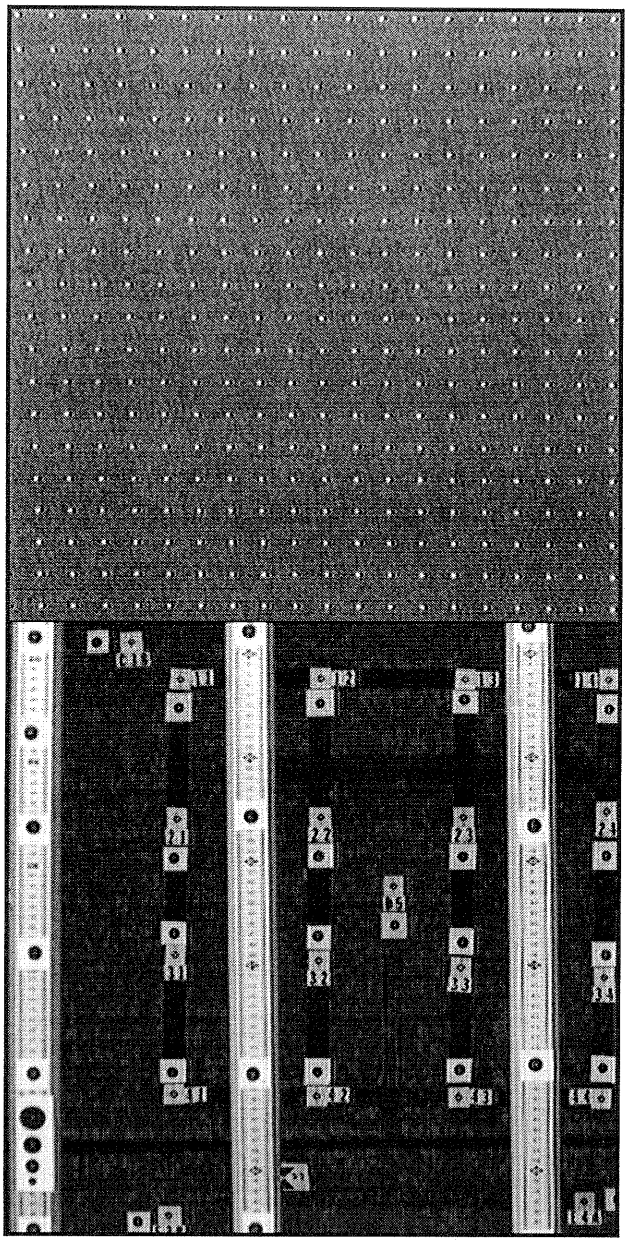

Figure 9: Laser projector based and testfield based targets.

repeatability measurement of testfield targets was affected by change in their size due to large depth of the testfield, while that of the laser dots was affected by speckle [Clarke & Katsimbris, 1994].

3 PROJECTOR MODEL

Active triangulation based systems have been used a number of times to solve the correspondence problem for automatic measurements of textureless objects. Light projection based active triangulation generally involves direct calibration [Trucco et al., 1994] of the whole system (black box type). Direct calibration consists of measuring the image coordinates of a grid of known three dimensional points, then look-up tables are built for the whole image through interpolation. In this calibration process there is no need to model any phenomena and this suits laboratory based machine vision applications. However, it is difficult to maintain the rigidity of the projector with respect to the camera during

Table 1: Deviation of observations of same points in different frames.

	No.	Min.	Mean	Max.	r.m.s.	Std dev
		Pixels	Pixels	Pixels	Pixels	Pixels
X*	361	0.00	0.027	0.309	0.046	0.042
Y*	361	0.00	0.023	0.251	0.042	0.038
x**	22	0.00	0.029	0.191	0.039	0.035
y**	22	0.00	0.0210	0.112	0.031	0.024

* = Active targets (laser dots) & ** = Targets of the testfield

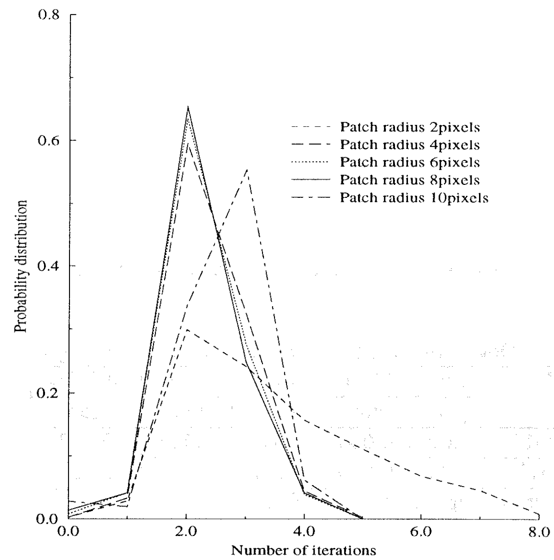

Figure 10: Probability of iterations with patch dimension.

field applications of a direct calibrated system. Such systems are not flexible enough to accommodate the varying depth and size of different close range objects. There is no standard method to calibrate such a system and generally such calibration requires a three dimensional testfield. Development of a standard photogrammetric camera model of the projector will probably be the best possible solution for these problems, and this has been attempted here.

3.1 Calibration

Rigid placement of the projector over the telescope of a geodimeter provided a good opportunity to measure the orientation of different dots of the projector. The use of a fixed spherical autoreflecting target helped in the precise and easy vertical placement of the laser dots over the target. Large numbers of geodimeter observations generated during calibration of interdot angles of the projector were communicated to the computer using a Psion organiser as a communication link. The interdot angles among the dot matrix of the projector were found to be quite stable over time and space. A simple statistical (Table 2) analysis of the deviation of two such observations over a five week period gave a reapitability of $\pm$ 0.01 gon.

3.2 Interior orientation parameters

Precise knowledge of focal length, position of principal point and lens distortion parameters are necessary for accurate three dimensional measurements of close range objects. In a system

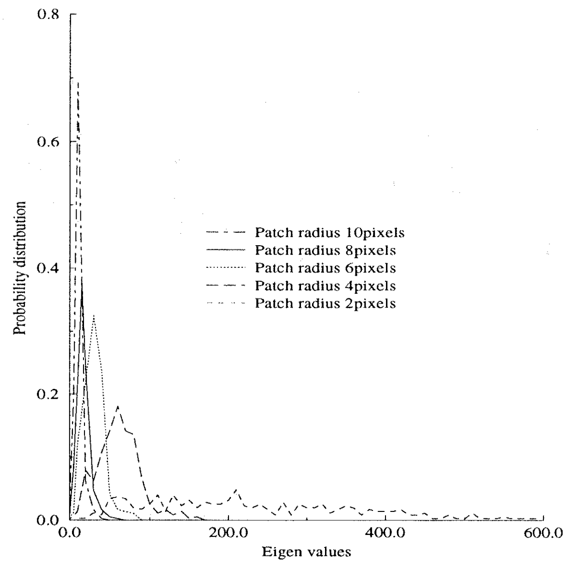

Figure 11: Probability of eigen value with patch dimension.

Table 2: Deviation of interdot angles of the laser projector.

No.	Min.	Mean	Max.	r.m.s.	Std dev
	gon	gon	gon	gons	gon
361*	0.00	0.008	0.047	0.016	0.013
361**	0.00	0.010	0.047	0.013	0.008

* = Vertical angle & ** = Horizontal angle

which uses a combination of a camera and a projector, these parameters for the camera are calculated using a standard test field or by fixing a CCD camera rigidly to the theodolite of a geodimeter [Huang & Harley, 1990]. The use of a projector as a second sensor creates a compatibility problem unless the projector is not treated like a camera. The projector makes it easy to solve the correspondence problem but three dimensional calculation of object co-ordinates becomes a little difficult or rather different from standard photogrammetric procedures due to the unavailability of the orientation parameters of the projector in a format of the real camera.

In establishing the reliability of the dot matrix projector, virtual three dimensional testfields were generated using two sets of observations of the geodimeter for two different distances from the fixed autoreflecting spherical target. Corresponding to each of these control targets an image co-ordinate was derived through the known regular pattern of the diffraction grating based dot matrix. The known positions of control points and their corresponding image co-ordinates were used for resection in the combined adjustment program (CAP) to calculate interior orientation parameters of the projector. The bundle adjustment results for the camera model of the laser dot projector were comparable with those of a real CCD camera (Table 3) which were derived using a standard three dimensional testfield. Due to the narrow field of view of the projector, the value of X and Y co-ordinates of the principal point were found to be highly correlated with phi (rotation about y-axis) and omega (rotation about x-axis) respectively. The lens distortion model of the laser projector showed relatively higher values of symmetric radial and tangential distortion but smaller values for decentric distortion compared

Table 3: Standard deviations of interior orientation parameters of the projector and the CCD camera.

Parameters	CCD camera	Laser projector
	Pixel	Pixel
Focal length (Std dev)	0.026	0.014
PP co-ordinate (Std dev)	0.026	0.063
K_1	0.475D-07	0.596D-04
K_2	0.543D-13	0.851D-07
K_3	0.932D-19	0.137D-09
B_1	0.195D-01	0.860D-03
B_2	0.123D-04	0.633D-03

to those of the CCD camera. The residuals after bundle adjustment for interior orientation parameters measurement of the CCD and projector are shown in Figure 12.

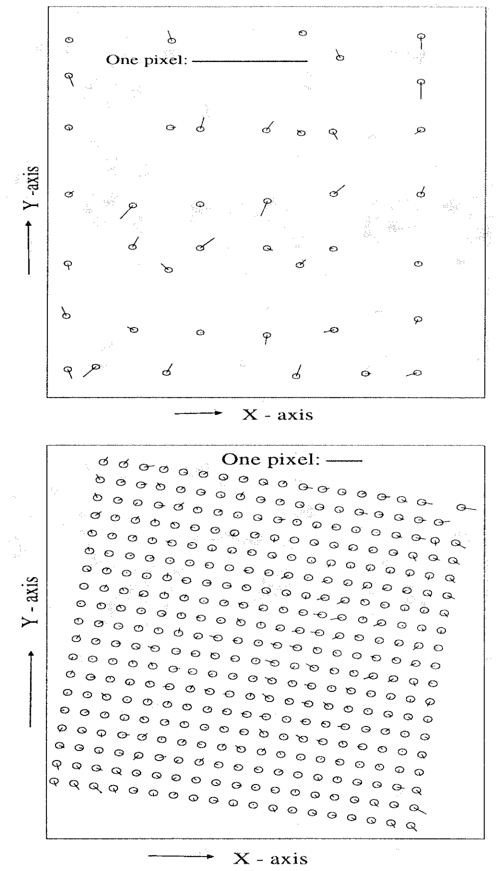

Figure 12: Residuals after bundle adjustment for camera and projector.

4 OBJECT SPACE MEASUREMENT

It is important to find the relative orientation of the projector with respect to the camera to obtain spatial intersection among the projected laser dots and their respective image co-ordinates. Both camera and projector are placed on the telescopes of geodimeters, so the relative orientation of one with respect to the other is measured by mutual pointing of the telescopes [Allan, 1993]. The distance between the two levelled geodimeters and the observations of their vertical and horizontal angles after mutual pointing are used for scaling

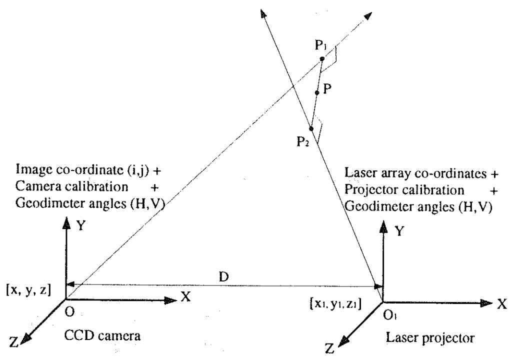

Figure 13: Spatial intersection for position estimation.

the intersection result. Different measurements to derive directions of any object point from the two positions contain observational and modelling errors, so exact intersection of all these rays is very difficult. In this system, estimation of the position of a target point is done by defining the middle point of the line normal to the two supposedly intersecting rays as shown in Figure 13. An intersection parallax 0.25 mm was observed during a laboratory test scan of an object at 4.5 m distance.

5 CONCLUSION

Simultaneous projection of a large number of distinct target points by diffraction grating based laser diode projector provides high accuracy for automatic measurement of a textureless object. Development of a camera model for the projector, treating it as a virtual camera, improves intersection accuracy during three dimensional object space co-ordinate measurement as various distortions are taken into account. There is no requirement for a three dimensional testfield for calibration of the projector and the camera which can be done in the field with the help of two known target points. Motor driven sensors can be handled remotely to scan large areas of object space. The knowledge of regularity of the dot matrix over a nearly flat object surface and the results of a suitable threshold for an uniform textured object surface may be used as initial estimates for fully automatic image co-ordinate measurements by least squares based template matching.

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