A Close Range Vision Cell for Direct Input to CAD Systems

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Abstract

A Close Range Stereo Vision Cell is described which is used to obtain high density, accurate 3D coordinates for shape characterisation of free form surfaces.

Since the final accuracy of the 3D coordinate data is dependent on the accuracy of the camera interior and exterior orientation parameters, the errors introduced through the use and calibration of CCD cameras has received particular attention.

1. Introduction

Real-time 3D measurement systems have a variety of potential applications, particularly within Computer Integrated Manufacture (CIM) **(Bhanu, 1987)**. Thorn EMI (TECRL) have a particular interest in the provision of 3D coordinate data to Computer Aided Design systems (CAD). The Close Range Stereo Vision Cell (CRSVC) has been constructed to develop the techniques required to achieve this aim.

The Alvey MMI-137 project has investigated the production of digital terrain models from stereo images provided by the SPOT satellite. **(Muller et al, 1988a)**. The CRSVC is designed to provide an alternative, real-time data source to the stereo algorithms developed under MMI-137, providing stereo images of industrial objects at close range. The design and calibration of the Cell has presented very different problems to those encountered in the satellite case, since the viewing geometry can give rise to occluded surfaces and large disparity ranges. Typical industrial objects have featureless, metallic surfaces which can create severe problems for the Otto/Chau stereo matching algorithm, which is based on adaptive least squares matching. **(Otto and Chau, 1988)** In order to overcome this we have experimented with the use of a projected, textured light system. **(Nishihara, 1984)**

2. System Configuration.

The cell consists of a rigid aluminium framework to which the cameras can be attached in a variety of configurations. The stability of the rig is important the ensure that there is no movement of the cameras between the calibration process and subsequent stereo pair acquisition. Objects up to 350mm square can be accomodated - the effective measuring volume is easily altered by a change of lens focal length and alteration of camera separation.

Two COHU 4710 CCIR frame transfer CCD cameras are connected with the TEMIPS **(Muller et al, 1988b)** framestore to provide rapid image acquisition. These images are then processed by the matching algorithm on a SUN-3 workstation. This configuration yields a data rate of 5 stereo matched points per second. The algorithms will eventually run on a PARSYS reconfigurable transputer array, which will increase the data rate to 2,000 points per second.

If the object to be measureed does not have sufficient natural surface texture, the textured light system can project a random dot pattern onto the object surface to assist the stereo matching process.

The disparity **(FIG. 1)** data provided by the matching algorithm is then re-projected through the camera model to provide the absolute 3D measurements. Currently the coordinate data is used to generate CAD models of sculptured surfaces which are generally very difficult to measure using a coordinate measuring machine **(Higashimoto, 1984; Hosaka, 1980)**. The task of determining high level descriptions for 3D object recognition and integration with existing CAD representations is considerably more complex **(Hoffman, 1987; Cohen et al, 1985)**.

The coordinate data is written to a file in a format suitable for direct input to the TECRL Computervision CADDS4X computer aided design system. Currently surface patches are built up manually by first linking points into approximately parallel B-spline curves which are combined into a collection of locally defined parametric surface patches.

Since the stereo matching and coordinate processing is planned to operate at near real-time, it is important that the calibration process be automated to enable rapid determination of camera parameters before a sequence of image pairs is prepared, and subsequent recalibration to ensure that these have not changed during image capture.

3. Camera Calibration.

The problems of calibrating metric and non-metric cameras are well known in photogrammetry **(Faig, 1971)**. More recently, as the emphasis on real-time systems has increased, attention has been given to the use and calibration of CCD cameras and the new problems that they entail. In general, however, the method employed has not changed **(Curry et al, 1986)**. A field of targets of known 3D coordinates is imaged and the camera parameters are obtained via a least squares adjustment. Since the collinearity equations, which relate 3D position in object space to 2D position in image space, are non-linear they must first be linearised using a set of approximate values for the unknown parameters and a first order approximation. An iterative solution for the corrections to the initial approximations is then carried out, until the corrections become negligibly small

An alternative method of obtaining the camera interior and exterior orientation parameters was proposed by Tsai **(Tsai, 1985; Lenz, 1987)**. His two-stage technique is based on the observation that, irrespective of radial lens distortion, the vector from the principal point to a particular image point is parallel to the vector drawn from the extended optical axis to the corresponding object space point. This technique offers a number of advantages over the traditional approach:

(1) The radial lens constraint allows the unknown parameters to be solved for in two steps (hence "two-stage"), each of which involves the solution of a set of linear equations

(2) because both steps are linear the technique does not require approximate knowledge of the values of the unknowns, which are always difficult to obtain with any non-metric camera

(3) the two-stage approach allows the use of a planar set of calibration targets, which is much easier to accurately manufacture and maintain than a three dimensional field.

(4) Tsai's model also allows us to consider the scale factor which defines the relationship between the number of samples along a line on the CCD array and the number of samples along a line in the framestore memory.

The principal point (PP), defined as the position where the optical axis of the lens intersects the imaging array, cannot be included as an unknown in this model. Ideally the centre of the imaging array (255.5, 255.5) would be taken as the PP, however this is unlikely to be the true position of the PP and we are therefore required to perform a pre-calibration measurement to determine the position of the principal point. These measurements are discussed below.

The Cohu CCD cameras are equipped with high resolution imaging arrays, which are 699 (v) * 575 (h) pixels. The cameras produce a standard CCIR 625-line interlaced video output of which only 575 lines contain active video information, the remainder are either blanked or are reserved for vertical sync. The digitiser samples the central 512*512 region of this information on a square grid.

The sampling frequency of the framestore does not neccessarily coincide with that of the camera. This requires the introduction of the scale factor discussed above. We currently operate with a scale factor of 67.5/75, though our set-up will shortly be altered to yield a scale factor of 1.0.

However, there is an additional problem with the transformation of the analogue video into digital memory. Each line of video information is predeeded by a line sync which signals the start of that line. It is possible for the digitising hardware to misinterpret the position of the line sync, from line to line **(Dahler, 1987)**. This can give rise to horizontal shifts between adjacent lines, an effect known as line jitter. We have conducted some experiments to give approximate figures for any jitter which may be present. These are also discussed below.

3.1. Measurement of Principal Point (PP)

Tsai outlines two techniques by which the position of the principal point can be determined, both of which we have investigated.

The first involves altering the focal length of the camera-lens system, this causes the image to expand outwards from a stationary point which is taken to be the PP. To achieve this we must alter the focal length by a reasonable amount, either by using a single zoom lens or two lenses of different focal length. Neither approach is satisfactory. In the first we must assume that all the elements of the zoom lens move along the optical axis. Alternatively if we use two different lenses then we assume that the position of the lens optical axis with respect to the camera lens mount is the same for both lenses.

The second technique outlined is a direct optical method and is similar in principle to auto-collimation. A laser beam is passed through a pinhole in a sheet of white paper and directed at the lens assembly mounted on the camera. The lens elements give rise to a series of multiple reflections which can be viewed on the paper. The position of the laser can be adjusted until all the the reflections coincide with the primary beam. At this point the laser is aligned with the lens optical axis, the camera is then switched on and the position of the laser point in the image is taken as the principle point.

We conducted a series of measurements in this way, using standard 16mm and 9mm focal length TV lenses. In particular we are interested in any variation in the position of the principle point with :

(a) focus adjustment

(b) different lenses

The results are shown in **FIG. 2** , which shows repeated measurements of the position of the PP using the direct optical method for two different focal length lenses, f=16mm and f=9mm.

There is a strong clustering of points obtained with both the 16mm and 9mm lenses. We can conclude that the position of the PP does indeed vary from lens to lens. In neither case does the PP correspond to the ideal image centre. The mean values of each set of measurements are taken to represent the PP for the 16mm and 9mm lens respectively. Altering the focus of a particular lens did not produce any change in the positions of the multiple reflections obtained from the lens elements, indicating that any variation of PP with focus is smaller than the spread of measurements obtained.

3.1.1. Importance of PP

The accuracy with which we need to know the position of the PP can be assessed by its effect on the accuracy of the final 3D measurement. Since this depends on how well we know the camera orientation parameters, the importance of the PP can be assessed by its effect on our knowlegde of these parameters. Various noisy data sets have been investigated and the results are shown in **FIG. 3** , which illustrates the error introduced into our knowledge of the Z position of the camera optical centre as a function of the accuracy with which we know the PP.

It can be seen that our knowledge of the PP must be within 10 pixels at least if we are to keep errors in the orientation parameters to an acceptable minimum.

3.2. Calibration Target.

One of the advantages of Tsai's approach is that it allows us to use a 2D field of targets.

Our cameras are calibrated by means of a 2D calibration plate consisting of a 500x750mm grid of 50mm spaced holes drilled in a cast aluminium alloy sheet. Flat top LEDs are fitted into the holes for use as active calibration targets. These are connected in a manner that enables two configurations to be illuminated; a near field configuration of 35 50mm spaced targets or a far field configuration of 40 100mm spaced targets. The use of a 2D field of calibration targets imposes certain limits on the positioning of the CCD cameras.

The image plane cannot be exactly parallel with the target plane, since in this orientation only the ratio :

$$\frac{\text{focal length } (f)}{Z \text{ distance}}$$

is well defined, and not the values of f and Z themselves.

In order to determine the optimum viewing position several experiments were conducted to examine the effect of the angle between the image plane and the calibration plane on the accuracy of the orientation parameters. Consider the error in the Z position of the camera optical centre. When the image plane and calibration plane are parallel this error is large, but drops rapidly as the viewing angle increases. However, as the viewing angle becomes more and more obliquethe errors introduced into the remaining orientation parameters begin to increase. The optimum configuration seems to be between 20 and 60 degrees.

3.3. Line Jitter

We have conducted a number of experiments to give estimates of the degree of line jitter present in our current system. These have involved measuring the image position of the centre of a carefully illuminated matt white bar, with the viewing position adjusted so that the image of the bar runs as close as possible to the position of the PP in order to decrease effects due to radial lens distortion.

The result of one such experiment is shown in **FIG. 4** The overall slope of the plot is due to the orientation of the bar wrt the pixel array, while gross effects, like that labelled, can be attributed to the image of the bar lying across pixel boundaries. It is important to realise that the remaining effects are due to a combination of factors such as residual lens distortion, image noise, illumination effects as well as possible jitter. However, it is hoped that these measurements confine possible jitter errors to the <= 0.3 pixel range.

In order to limit the possibility of jitter as much as possible we plan to experiment with our camera/framestore synchronisation. In particular we wish to either,

(1) drive the CCD cameras with horizontal and vertical syncs from the framestore

or

(2) use the pixel clock from one camera to drive both the remaining camera and the sampling of the framestore A/D.

4. Conclusion

Our initial system for the capture of 3D coordinate data has been described. The importance of camera calibration, and our efforts to limit errors arising from this process, has been discussed.

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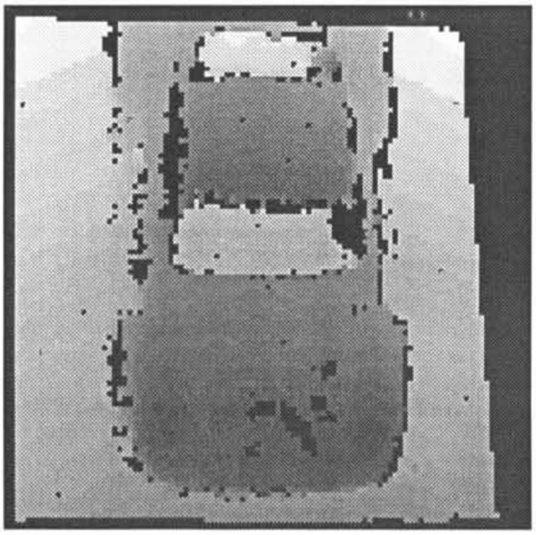

Fig.1. Range data from CRSVC

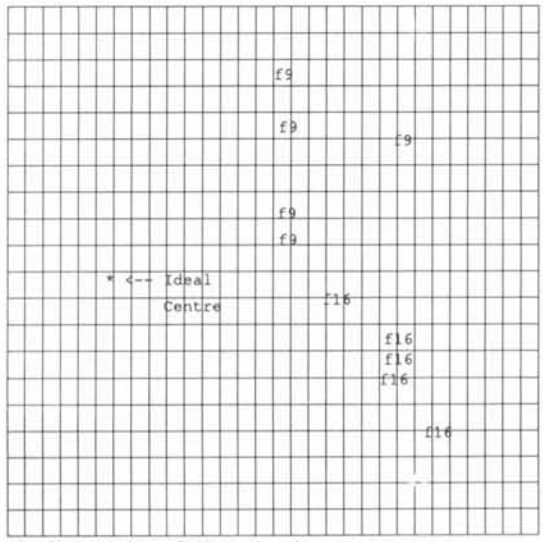

Fig.2. Position of PP on imaging array

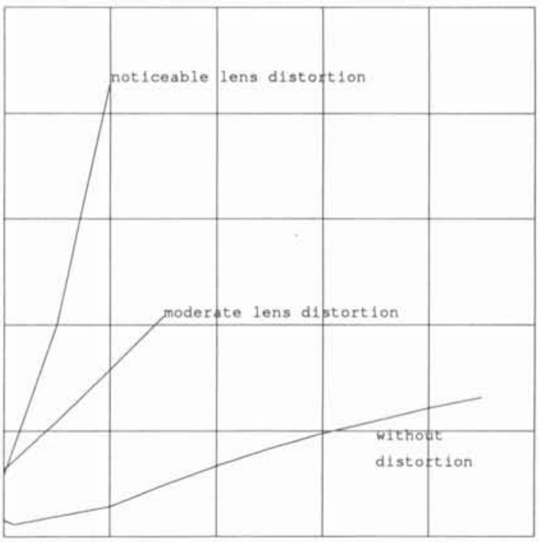

Fig.3. Error in Z position of Vs. Accuracy of PP

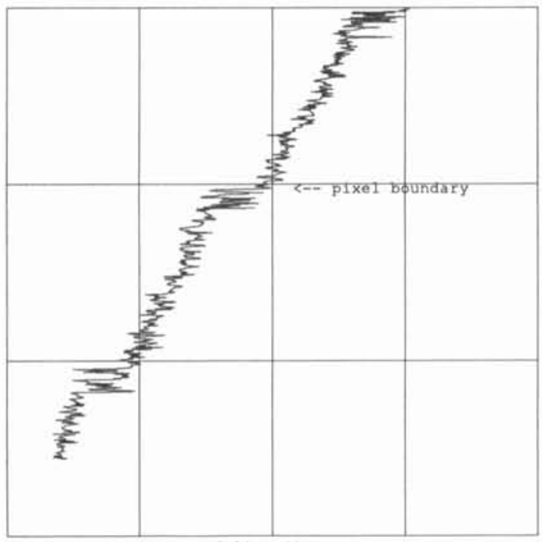

Fig.4. Measurements of line jitter

Fig.1. Disparity data, obtained by matching stereo images of a model porsche.

Fig.2. Measurements of the position of the PP by the direct optical method for two different lenses, f = 16mm and f = 9mm. The ideal image centre (255.5,255.5) is shown. Grid spacing corresponds to one pixel in both X and Y.

Fig.3. Error in Z position of optical centre, in mm, ploted against the accuracy of the PP, in pixels, for various lens distortions. Grid spacing on the Y axis is 20mm (0 to 80mm), while that on the X axis is 10 pixels (0 to 50).

Fig.4. Measurements of line jitter. Grid spacing on the Y axis is 200 image lines (0 to 600), while the X axis grid spacing is 1 pixel.