

Calibration Tests of Industrial and Scientific CCD Cameras

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Abstract

Small format, medium resolution CCD cameras are at present widely used for industrial metrology applications. Large format, high resolution CCD cameras are primarily in use for scientific applications, but in due course should increase both the range of applications and the object space accuracy achievable by close range measurement. Slow scan, cooled scientific CCD cameras provide the additional benefit of additional quantisation levels which enables improved radiometric resolution. The calibration of all types of CCD cameras is necessary in order to characterise the geometry of the sensors and lenses. A number of different types of CCD cameras have been calibrated at the NASA Langley Research Center using self calibration and a small test object. The results of these calibration tests will be described, with particular emphasis on the differences between standard CCD video cameras and scientific slow scan CCD cameras.

Introduction

Camera calibration has been and will always be a necessary part of the photogrammetric process. Knowledge of the internal geometry of the camera is essential if the principle of collinearity is to be correctly applied. Without this knowledge, derived measurements in the object space will be affected by systematic errors and therefore will be degraded in accuracy. Whilst in many circumstances self calibration may be feasible, in some cases such an approach is not appropriate. Self calibration is typically ruled out because the geometry of the photogrammetric network is too weak to determine the calibration parameters with confidence or with a reasonable degree of independence. The internal characteristics of the camera must therefore be determined before or after the actual measurement process.

Calibration considerations are of course not confined to conventional cameras using photographic emulsions. Since their introduction in the 1970s, CCD cameras and digital images have gained increasing acceptance for machine vision and industrial metrology. The very nature of the tasks in which CCD cameras are employed tends to exacerbate rather than ameliorate the calibration problem. Real time or near real time applications require multiple, fixed (and synchronised) cameras, whereas self calibration is most effective with a single, mobile camera. Further, such applications often involve small numbers of targets, whereas a dense, three dimensional array of targets which fills the camera format vastly increases the effectiveness of self calibration.

Pre- or post-calibration can be carried out by a variety of techniques. Using an established test range, comprising a two or three dimensional array of suitable targets with known coordinates, and multiple photographs is perhaps the most common method and has been used for virtually all types of cameras (Curry et al, 1986; Earls, 1983; Merchant and Tudhope, 1989). However, known target coordinates are not always necessary. If the geometry of the photogrammetric network is sufficient (Shortis and Hall, 1987) and only the primary physical calibration parameters are desired then the situation reverts to a self calibration. The

calibration is in effect taking advantage of a better network geometry which can not be obtained during operational photography. Although it is advisable to include an accurate distance between two targets to correctly scale the network, even this minimum information is unnecessary for self calibration.

Laboratory calibration is the main alternative to test range or self calibration if a full set of calibration parameters is required. Laboratory techniques can be based on multicollimators (Carman and Brown, 1978) or goniometers (Ziemann, 1978), or can be a component analysis approach which is based on optical bench tests (Burner et al, 1990). These approaches suffer from the disadvantage that the camera is not in the normal environment or mode of operation whilst it is tested, which raises the question of whether the calibration is representative for operational photography. The clear advantage of laboratory calibrations is that the derived calibration parameters are virtually independent.

Other techniques are generally partial calibrations which derive a subset of parameters. The plumb line calibration method was originally developed by Brown (1971) for close range cameras, but has been successfully applied to aerial (Hentschel and Shortis, 1991), tube type video (Burner et al, 1985) and CCD video cameras (Fryer and Mason, 1989). This technique is capable of deriving the lens distortion parameters independently from all other parameters, and can be carried out under operational conditions. Many specialised techniques have been developed to empirically or analytically derive particular aspects of the internal geometry of cameras. For example, Lenz (1987) used target tracking to determine the principal point location and a 2D point array to determine radial distortion of a zoom lens on a CCD camera, Tsai (1986) developed a minimal set of exterior and interior parameters to calibrate CCD cameras for machine vision applications, and the DLT approach to combined exterior and interior orientation of cameras is widely used (Burner et al, 1985).

CCD Camera Calibration at NASA Langley Research Center

Modern close range photogrammetric techniques have been in use at NASA Langley Research Center (LaRC) for more than ten years. State of the art large format metric camera approaches are used to characterise large space structure components (Shortis, 1989). Photogrammetric techniques for wind tunnel testing initially used synchronous stereophotography with conventional non-metric cameras to measure deformations of wind tunnel models under test conditions. Recent developments have focussed on utilising video based systems both to provide access to hostile environments and to avoid tedious processing and measurement of film based systems. Analog video cameras are also being replaced with solid state cameras to ameliorate troublesome vibration problems often encountered in applications. Burner et al (1987) describes the evolution of a CCD camera system currently installed in the National Transonic Facility.

The requirement for pre- or post-calibration of CCD cameras at LaRC is a direct result of applications such as wind tunnel testing. The placement of cameras and target arrays is severely limited within the test zones of wind tunnels and self calibration is rarely possible due to the constraints on network geometry. To capture the images in real time during model tests there is mandatory requirement for multiple, fixed cameras, which further reduces the effectiveness of self calibration.

Due to these limitations, simple resection/intersection techniques are in use at LaRC as appropriate to the task at hand. However, there is continuous pressure on wind tunnel instrumentation to improve the accuracy of measurement in accord with more stringent engineering tolerances. This pressure has generated increased interest in the modelling and elimination of systematic errors, which in turn has resulted in the necessity of comprehensive camera calibration.

Optical bench techniques to calibrate CCD cameras have been under development at LaRC for several years (Burner et al, 1990). As noted above, this technique has the advantage that the calibration parameters are acquired independently, but has the disadvantage that the camera must be disassembled and is not in the

normal operating mode. Optical bench testing gives a comprehensive calibration, but is labour intensive and requires alignment and measurements which are time consuming (and can introduce additional error) when compared to self calibration. Because of these disadvantages and due to the increasing number of CCD cameras at LaRC, self and test range calibrations of CCD cameras are being investigated.

The Test Range Calibration Approach

The use of test ranges to calibrate CCD cameras has been successfully implemented by a number of researchers (Beyer, 1987; Bösemann et al, 1990; Gustafson, 1988; Wiesel and Voegtle, 1986). In order to confidently derive the calibration parameters, the geometry of the network should be essentially the same as that required for a self calibration. The technique of self calibration was first adopted in the late 1960s, has been universally accepted for industrial and engineering applications, and was adopted at LaRC in the 1980s for conventional photography (Shortis, 1989). Multiple, convergent photographs of the target array are taken, preferably with a range of camera to object distances and a variety of roll (rotation about the camera axis) angles to reduce correlations between parameters. The target images are observed manually or measured by digital image processing. The reduction and analysis is based on the principle of collinearity and an iterative solution by least squares estimation.

Self calibration is the accepted technique for the modelling and elimination of small systematic errors which would otherwise detrimentally affect the accuracy of the measurements. Self calibration typically employs primary parameters to model physical imaging system characteristics such as principal point location, principal distance, lens distortions, and either physical, empirical or a combination of types of additional parameters to model image non-linearities and image plane unflatness (Faig and Shih, 1988).

Photography of test ranges composed of targets with known coordinates introduces additional external constraints. The external constraints are conveniently incorporated into the least squares estimation process via sequential adjustment, also known as a priori weights (Case, 1961). External constraints are important if the non-linearities and unflatness of the image medium must be derived. Block-invariant parameters, which should be applied to CCD cameras because of the stability of the sensor, will not be confidently determined unless there are external constraints supplied by targets with known coordinates. Otherwise the signal from non-linearities and unflatness will be absorbed into the random noise of the image measurements, leading to a slight inflation of the residuals (Fraser, 1987).

Camera Types

Four different types of CCD sensor have been calibrated using the test range technique at LaRC. The characteristics of these cameras are shown in Table 1. The Cohu camera has a medium resolution sensor which is generally representative of CCD cameras used for machine vision and industrial measurement. The Toshiba camera is a physically small, short focal length unit which might be used for robot vision or low accuracy industrial applications.

The Kodak and Thompson cameras are classified as slow scan, scientific CCD sensors. The slow scan allows very low noise, maximum CCD performance and optimum radiometric precision. Trinder (1989) discusses the effects of grey level on the precision of locating digital targets. The slow scan cameras are cooled to reduce dark current to very low levels compared to standard video rate cameras, thus allowing very long exposures such as those needed for astronomical applications. The slow scan cameras have several operational differences, compared to standard video cameras, which make them more difficult with which to work. For example, a complete image from the Thompson sensor takes approximately 20 seconds to acquire, so focussing must be accomplished using only a small part of the image. Also note that a complete image from the Thompson requires 2Mb of computer storage. These operational difficulties and the significant

increase in cost over standard video cameras should generate some reluctance to choose a slow scan camera for all but the most demanding digital photogrammetric applications.

<i>CCD Sensor</i>	<i>Toshiba</i>	<i>Cohu</i>	<i>Kodak</i>	<i>Thompson</i>
Resolution (pixels)	570H 485V	752H 484V	1035H 1320V	1024H 1024V
Pixel size (μm)	11.4H 10.0V	11.5H 13.5V	6.8H 6.8V	19.0H 19.0V
Format size (mm)	6.5H 4.8V	8.8H 6.6V	7.0H 9.0V	19.5H 19.5V
Focal length (mm)	8	25	50	50
Digitised pixels	752H 480V	752H 480V	1035H 1320V	1024H 1024V
Quantisation (bits)	8	8	12	14
Grey levels	256	256	4096	16384
Cooled sensor	No	No	Yes	Yes

Table 1. Characteristics of the calibrated CCD cameras

Data Acquisition

Eight frames of a small test object were taken with each camera. To facilitate the frame acquisition, the camera was held fixed and the test object was rotated. The camera was rolled about the optical axis by 90° after each frame. The geometry of each network in each case was essentially the same (see Figure 1) and adhered to the optimal geometry proposed by Fraser (1986).

The camera to object distance was set in each case to maximise the coverage within the format of the sensor, without target image losses for any frame. The resultant image scales were consistent for the Toshiba, Cohu and Kodak cameras because of the comparable format sizes, whereas the larger format Thompson sensor allowed a considerably larger image scale.

The test object is a rectangular box with targets on one face only. The targeted aluminium face is approximately 0.4m by 0.3m and has an array of 54 retro targets, each 3.2mm in diameter. Data acquisition required several minutes for the Toshiba and Cohu calibrations and about 30 minutes for the Kodak and Thompson calibrations. Typically the laboratory temperature is stable to better than 1°C over such short periods of time, hence it is extremely unlikely that the box would change significantly in size during the time required for a calibration test. The targets on the surface have been independently coordinated using a number of methods. Initially the targets were measured using a 3D coordinate measuring machine to an accuracy of 0.05mm. The coordinate data used for the testing is based on a self calibration network using a CRC-1 camera, TechPan film and an Autoset-1 comparator. The mean coordinate precision of the targets from this network was 0.0054mm.

The target array on the test object is two dimensional. Early tests with additional points to create a three dimensional array showed that the improvement in the precision of and the reduced correlation between the calibration parameters did not justify the extra effort of maintaining a more complex test object. This is, in part, due to the very strong geometry of the calibration networks and the large number of redundancies (620 for the self calibration networks and 780 for the test range networks) in the least squares estimation solution.

A fluorescent ring light or a ring of eight diodes were mounted coaxially with the camera lens to illuminate the retro targets. The intensity of the lighting could be varied using a rheostat control, and in every case the grey levels were checked to maximise the signal from the targets whilst avoiding saturation of the sensor. The use

of retro targets enables the background image to be kept at low intensity relative to the target signal, hence sophisticated pattern recognition routines to unambiguously isolate the target images are unnecessary.

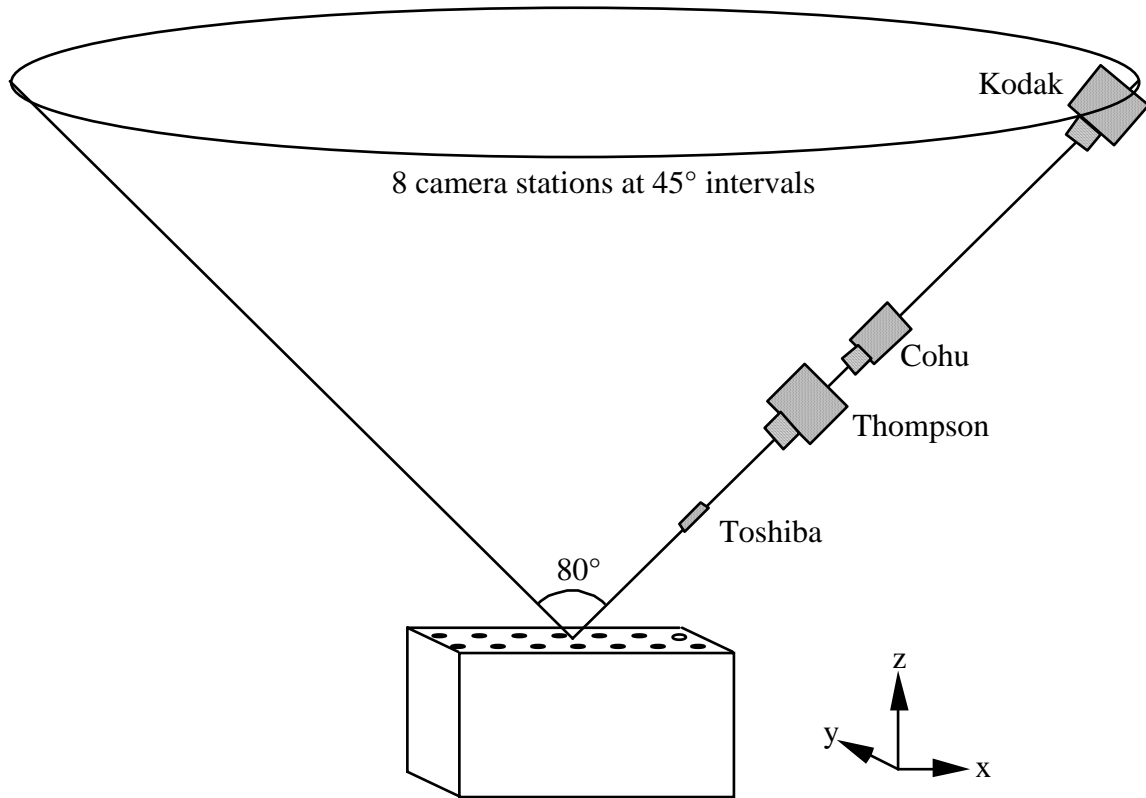


Figure 1. Geometry of the calibration networks (not to scale)

In every case the cameras were allowed at least two hours to reach thermal equilibrium before the calibration test commenced. For the Toshiba and Cohu video cameras the frames were grabbed by an Epix 4 Mb MUX frame grabber board. The horizontal and vertical synchronisation of the Epix frame grabber board was derived (genlock on) from the Toshiba and Cohu video cameras for their respective calibration tests. The digitisation of the Epix board was locked by the pixel clock for the Cohu calibrations. For the Toshiba camera the analog video signal derived from the 570 sensor pixels was digitised by the frame grabber into 752 pixels. The Kodak and Thompson cameras are true slow scan, cooled, scientific CCDs commercially available from Photometrics Ltd. The scan rates are 200KHz and 50KHz respectively, as compared to the 14.318MHz video rate for the Toshiba and Cohu sensors.

The target images spanned between 5 and 7 pixels on average. The images are located within the frame using a semi-automated procedure based on the known object space coordinates of the targets. Initially the operator is required to manually select a minimum of three targets, using a cursor and video monitor, to determine a resection for the frame. Subsequently the software automatically locates all remaining targets. The size of the window used for the location procedure can be varied depending on the reliability of the object space coordinates and the knowledge of the lens calibration parameter set.

Within each target window the pixel intensities were first tested against a threshold computed according to Wong and Wei-Hsin (1986) :

$$\text{Threshold intensity} = \frac{\text{minimum intensity} + \text{mean intensity}}{2}$$

Pixels below this threshold were set to zero. In general the estimation of the threshold worked successfully. Occasional images from Cohu frames required operator intervention because of drop outs, that is pixels which falsely registered as zero. As the background level was typically 10% of the peak intensity, a minimum intensity of zero would result in an inappropriate threshold.

The weighted centroid of the target image was then computed using the remaining non-zero intensity pixels inside the window (Trinder, 1989). More complex image location schemes, such as template matching or intensity profiles, are probably not warranted here because of the very "clean" images supplied by the retro targets. Finally, the location of the image was converted from the units of pixels to the units of millimetres via the specified pixel spacing of the sensor.

Self Calibration Processing

The image data from the CCD cameras was processed using the CRAMPA suite of programs (Shortis, 1989) executed on a Sun Sparcstation under Unix. Initially the data sets were treated as self calibration networks, each with an implicit datum supplied by internal constraints. There were no rejections of image observations from any network.

A comprehensive set of block-invariant physical and empirical additional parameters was included in the network adjustment in each case, and progressively refined by rejecting insignificant and correlated parameters. The parameter set comprised physical terms for principal point location, principal distance and lens distortions of the lens optics, as well as physical terms for the orthogonality and affinity of the sensor. The parameter set also incorporated a polynomial series with high order, empirical terms to account for image non-linearities and image unflatness. The polynomial series used is derived from the high order terms described in Brown (1976). This type of parameter set gave the most favourable results for close range and aerial conventional photography when compared to a number of other parameter sets (Murai et al, 1984; Faig and Shih, 1988).

<i>CCD Sensor</i>	<i>Toshiba</i>	<i>Cohu</i>	<i>Kodak</i>	<i>Thompson</i>
Image scale	1:80	1:75	1:70	1:25
RMS image error (μm)	0.75	0.35	0.13	0.28
RMS image error (pixels)	0.070	0.028	0.019	0.015
Significant non-phys. APs	3	2	1	1
Relative precision	1:13,000	1:26,000	1:53,000	1:111,000
Mean target σ_{xyz} (mm)	0.035	0.018	0.009	0.004
RMS check error (mm)	0.053	0.028	0.021	0.014
Mean target σ_{xy} (mm)	0.030	0.020	0.011	0.005
Mean target σ_z (mm)	0.045	0.013	0.005	0.004
Ratio of σ_z to σ_{xy}	1.52	0.67	0.45	0.84

Table 2. Results of the CCD camera self calibrations

The results of the processing of the four data sets are shown in Table 2. Because there are no external constraints, these results represent internally consistent networks with optimal RMS image errors and optimal relative precisions (the ratio of the mean target coordinate precision to the longest dimension of the object). Comparison of the RMS image errors (in pixels) of the Toshiba versus the other sensors shows the clear improvement gained by better synchronisation. The expected improvement from better grey scale sensitivity is apparently demonstrated. The Thompson sensor realises a relative accuracy previously only possible with conventional film cameras.

However, an analysis was conducted of the 14 bit Thompson data to assess the importance of grey level on image plane residuals. This simple analysis indicated very little difference in image plane residuals for weighted grey level centroiding when treating the 14 bit Thompson data as if it were 8 bit. The centroids for the 14 bit images reduced to 8 bits agreed with the original 14 bit centroids to within 0.003 pixels. Similar results were found when using the 14 bit reduced to 8 bits in a self calibration reduction. The image plane residuals agreed to better than 0.01 micrometres (0.005 pixels). These results are in general agreement with the theoretical results of Trinder (1989), but the implication here is that the extra grey levels do not fully account for the improvement in centroid accuracy.

The precisions of the derived principal distances of the cameras, for example, varied from 4 to 12 micrometres, whilst the average parameter correlation factor was 0.15. Other than the physical parameters of principal point location, principal distance and lens distortions, all cameras required at least one additional parameter. Only the affinity parameter was significant for the Kodak sensor, whilst there were significant orthogonality, affinity and a higher order term for the Toshiba sensor. As expected, the Kodak sensor exhibited virtually zero lens distortions. The focal length to format ratio is such that only the central region of the lens field of view is utilised.

The RMS check errors shown in Table 2 represent the accuracy of the self calibration networks tested against the CRC-1 derived values for the target coordinates. In every case the RMS check (corrected for the precision influence of the CRC-1 data) is larger than the mean precisions predicted from the photogrammetric network, indicating the presence of unmodelled systematic errors or over-parameterisation of the least squares estimation solutions. Tests with minimum sets of additional parameters (principal point coordinates, principal distance and one radial distortion parameter) showed no significant improvement. This result implies that there is a source of systematic error present and over-parameterisation is not the problem.

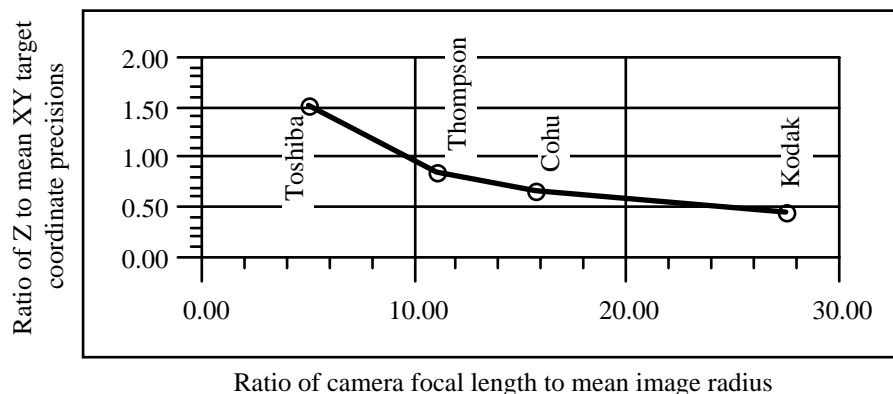


Figure 2. Self calibration precision ratio versus the ratio of the camera focal length to format size

An unusual feature of the results for the target coordinates is the ratio of the mean Z precision to the XY precision. Under normal circumstances a network with 8 camera stations and a convergence angle of 80° would be expected to produce a ratio of near unity (Fraser, 1986). However the Cohu and Kodak cameras produced ratios significantly less than unity, and there is an definite correlation between the precision ratio and the ratio of focal length to format size for the camera. A graph of the precision ratio against the ratio of the focal length to the mean image radius (Figure 2) confirms this supposition. There is no ready explanation for the mechanism of this phenomenon and it is therefore worthy of further investigation.

Test Range Calibration Processing

The image data was again processed using CRAMPA. In this case the data sets were treated as test range calibration networks, each with an explicit datum supplied by external constraints. The à priori coordinates of the targets, from the CRC-1 network, were incorporated using sequential adjustment. Again a comprehensive set of block-invariant physical and empirical additional parameters was included in the network adjustment in each case, and progressively refined by rejecting insignificant and correlated parameters.

The results of the processing of the four data sets are shown in Table 3. Again there were no image rejections. As could be expected, there were significant changes in the values of the derived calibration parameters and significant improvements in the precisions of the derived calibration parameters. The average correlation factor between calibration parameters was marginally reduced to 0.14.

<i>CCD Sensor</i>	<i>Toshiba</i>	<i>Cohu</i>	<i>Kodak</i>	<i>Thompson</i>
RMS image error (µm)	0.88	0.45	0.20	0.39
RMS image error (pixels)	0.082	0.036	0.029	0.021
Significant non-phys. APs	3	2	1	0
RMS check error (mm)	0.001	0.003	0.006	0.007

Table 3. Results of the CCD camera test range calibrations

In every case the RMS image error has increased significantly whilst the RMS check errors have decreased to or below the noise level in the coordinates derived from the CRC-1 network. The contrast in results between the Toshiba and the other three sensors is again evident. The consistency of the RMS image errors for the Cohu, Thompson and Kodak sensors indicates that the accuracy of the technique used to locate the centroids is limited to 0.020 to 0.035 pixels, dependent on the quantisation level. The degradation of the RMS image error suggests that use of the test range has detected unmodelled systematic errors in the data which were not evident in the self calibration networks.

It should be noted however, that even with the degraded centroid accuracy, the result for the Thompson CCD camera represents a relative accuracy of 1:80,000. This is a considerable improvement in accuracy over medium resolution CCDs such as the Cohu camera, which are generally in the 1:10,000 to 1:20,000 range.

Conclusions

The results obtained by this investigation and other researchers clearly demonstrate that test range calibration is a precise and reliable method of calibration for CCD cameras. The calibration parameters are derived with acceptable precision and sufficient independence to be carried forward to operational use where self

calibration of the camera is not feasible. However further investigation into the source of the systematic errors detected by the calibrations is prerequisite to absolute confidence in the results. In particular, different types of additional parameter sets should be tested. A more appropriate parameter set may be able to determine whether the systematic errors are a characteristic of the sensors. The impact of quantisation on centroid accuracy should also be subjected to further investigation by experimental testing.

However, the improvement in the RMS image errors for the scientific CCD sensors, as compared to the lower resolution, non-cooled sensors, indicates that the greater radiometric sensitivity and lower noise does enhance the accuracy of the image location. Stanton et al (1986) reported RMS image errors for centroiding as low as 0.01 pixels using a scientific sensor, albeit with a back side illuminated CCD. The simplistic approach of estimated threshold and weighted centroid used here does not take sufficient advantage of the more sophisticated scientific sensors. Strategies such as subtraction of the average bias field, removal of dark field trending and flat field calibration are the subject of continuing investigations in order to improve the centroiding accuracy. RMS image errors at the level of 0.01 pixels, as compared to the 0.02 pixels achieved here, would allow scientific CCD cameras to be applied to engineering and industrial measurement tasks with significantly more stringent tolerances. The implication for the Thompson CCD camera is a relative accuracy of the order of 1:200,000.

Furthermore, CCD cameras can make use multiple photographs to improve object space accuracy and precision in cases where self calibration is feasible (Shortis, 1988). Images can be rapidly and economically stored, as the speed and cost of computer storage media continue to improve, or the image centroids can be computed in real time or near real time, as the raw computational power of computers and frame grabbers also continues to improve. Such research and development will inevitably lead to large format, scientific CCD camera systems which are capable of achieving the accuracies which are presently the exclusive province of conventional cameras. A portable industrial measurement system based on a cooled scientific CCD camera is feasible and would have a number of advantages over the exiting systems based on conventional cameras. Of particular significance would be the substantial decrease in the time required to produce object space coordinates. The development of CCD sensors with up to 4096 by 4096 pixel arrays (Janesick et al, 1990) will hasten these advances.

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