The influence of storage media on the accuracy and repeatability of photogrammetric measurements using CCD cameras

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ABSTRACT

A clear advantage of digital photogrammetric measurement over other, more conventional techniques is the fast sample rate of the data acquisition. CCD cameras and video systems can be used very effectively to analyse dynamic objects or cases of rapid deformation. However, long sequences of images can introduce the penalty of large volumes of digital data, which may not be able or appropriate to be processed in real time. The images are typically stored in analog form, using media such as video tape or video disk, for off line processing subsequent to the image capture. This paper investigates the degradation in accuracy and repeatability caused by the influence of the analog recording. A number of experiments using a Hitachi medium resolution CCD camera, a three dimensional test range and a self calibrating bundle adjustment are described. For cases of near real time monitoring, the ability of frame averaging to reduce the degradation caused by the analog recording is also investigated. The results of the experiments are presented in summary to provide some guidelines as to the degree of degradation which can be expected under similar circumstances.

1. REAL TIME CAPTURE

The ability to capture digital data in real time is the essential advantage of CCD cameras over conventional film based camera systems. Moreover, the data can be captured at a relatively fast sample rate of 25 or 30 frames per second, allowing the measurement and analysis of dynamic processes or rapid deformation. The real time capture and fast sample rate has been exploited to great effect by the machine vision and, more recently, the close range photogrammetry communities. Both two and three dimensional measurement tasks are carried out routinely over a wide range of applications.

However, unless the measurement is a relatively straightforward task under controlled conditions, real time processing and analysis requires more computer processing power than can be made conveniently available. Although advances in technology are broadening the range of image processing computations which can be carried out at frame rate, very complicated metrology applications are beyond the current capabilities of machine vision systems. For example, if multiple targets are to be continuously tracked and located in three dimensional space using multiple CCD cameras, then the task is generally relegated to near real time or not real time processing. The lesser options may be selected either because the environmental conditions are not favourable, the requirement for online storage of images or image sequences is unacceptable, or because the cost of a real time system for frame rate processing is not warranted by the application.

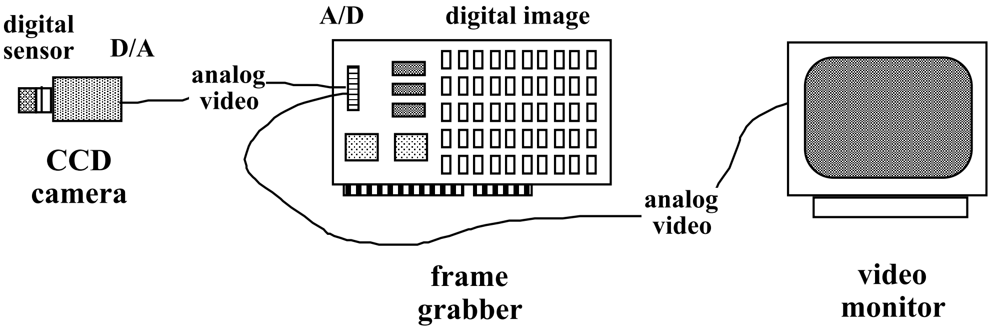


Figure 1. Direct CCD image acquisition for real time or near real time processing.

Near real time is defined as below frame rate, but still with a real time response as far as the analysis is concerned. Systems with update rates between half frame rate and several minutes could be included in this category, as long as the response time is sufficient for the application at hand. Both real time and near real time systems directly acquire the digital image information via an immediate frame grab and carry out the required processing without intermediate steps or processing phases (see Figure 1). Not real time systems are identified by the use of off-line storage of the images. In such cases the images are recorded on a suitable medium for later play back and analysis (see Figure 2). Both real time and near real time systems may also record the images, but only for archival storage. Not real time systems post process the data using the recorded images because the recording medium is convenient for storage of large volumes of image sequences.

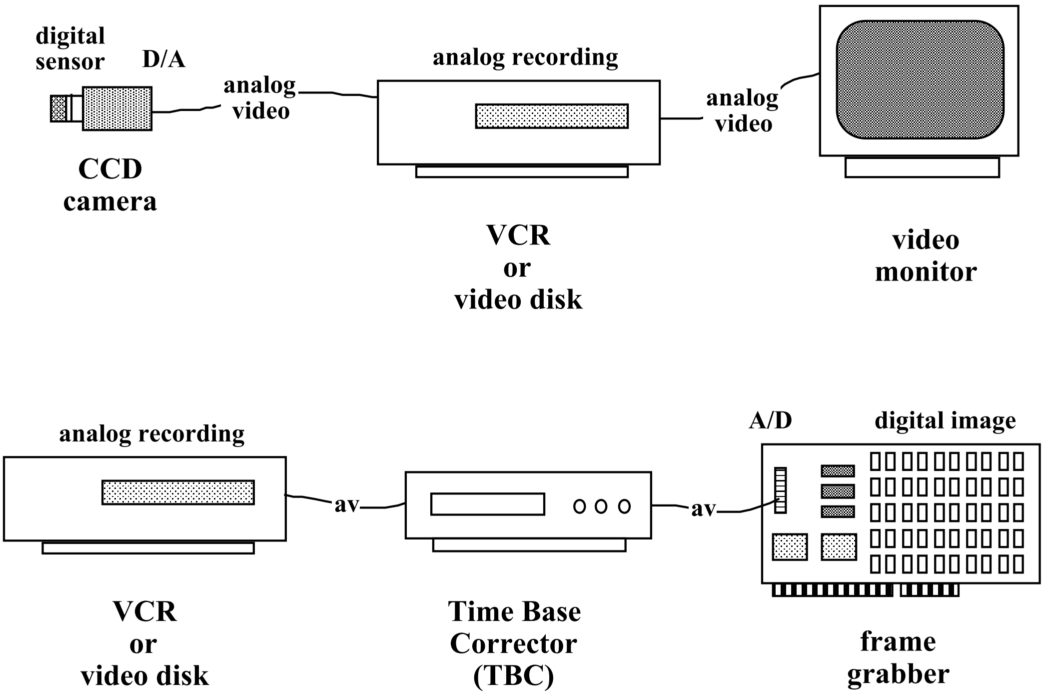


Figure 2. The two stages of indirect CCD image acquisition for not real time, off-line processing.

An example of a circumstance where not real time systems are appropriate is the wind tunnel testing of aerospace models carried out at NASA Langley Research Center[3,7]. The measurement of the deformation of flight surfaces or the location and orientation of models in real time requires multiple targets to be located on multiple images at frame, or sometimes field, rates. Although it is possible to derive limited information at frame rates using powerful computer systems, complete and reliable characterisation of the deformation or location and orientation in real time is currently cost prohibitive.

In such circumstances the fall back position is to record the CCD imagery, suitably synchronised, using standard video systems. The standard adopted at Langley is Super VHS (S-VHS) because it has the highest horizontal resolution and bandwidth of the available "off the shelf" systems[5]. Images can be recorded at frame rate using either high quality video tapes mounted in video cassette recorders (VCR) or 12" video disks mounted in video disk recorders. Both of these media record a standard analog video signal (video disk technology is not yet digital and is not compatible with computer optical storage systems such as CD-ROM and WORM drives), but video disks have the advantage of random access to individual frames. Video images are frame grabbed off the recording, rather than acquired directly from the CCD camera, and post processed subsequent to the image acquisition.

The question which immediately arises is what influence does the recording medium have on the integrity of the images from the CCD camera? This question is particularly pertinent to wind tunnel testing of aerospace models because of the stringent tolerances specified in many cases. Direct acquisition is the base line against which video recording and off-line processing should be measured, as this is the best case scenario. Yet in many instances model measurement using CCD video systems is marginal in terms of object space accuracy. Hence any deterioration in accuracy caused by media degradation of the CCD images is critical to the viability of the technique.

2. DEGRADATIONS CAUSED BY RECORDING MEDIA

The issue of synchronisation of images from CCD cameras has been thoroughly researched in the case of direct acquisition[2]. Synchronisation uncertainty is fundamental to the nature of the analog video system which transmits the CCD images from the camera to the frame grabber or video recorder. Synchronisation errors may cause displacements of the entire frame, or displacements of the individual horizontal scan lines which make up the image frame. Displacements of the entire image can be compensated by adjusting the calibration of the CCD camera, but scan line displacements affect the integrity of the image because of their pseudo-random nature.

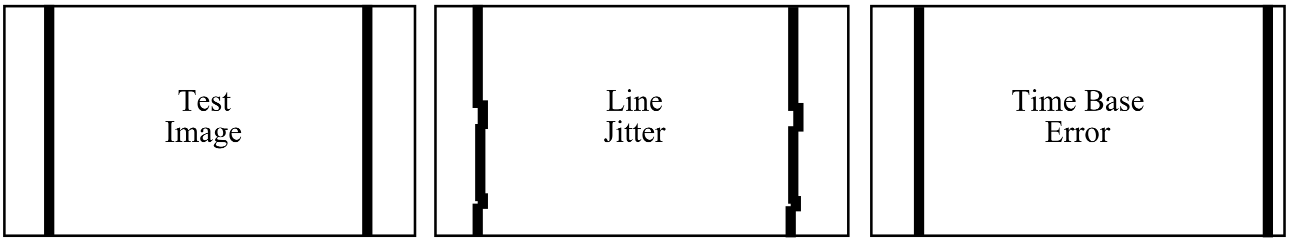


Figure 3. Indicative effects of line jitter and a constant time base error on a vertical line test image.

Known as line jitter, scan line displacements will cause a vertical line in a video image to show discontinuities (see Figure 3) of the order of tenths or hundredths of a pixel. The loss of integrity of the image, and consequent loss of accuracy in the object space, is directly proportional to the magnitude and frequency of occurrence of line jitter.

As recording of images using video disk or tape requires at least one extra synchronisation, it could be predicted that line jitter errors are likely to increase. Additional steps in the acquisition, recording and play back system will inevitably result in greater magnitude and frequency of synchronisation errors. Different synchronisation schemes or pixelsynchronous sampling reduce the effect of line jitter, but this option is available only to direct acquisition by frame grabbers and cannot be used in conjunction with standard video recording systems.

An available method for correcting synchronisation errors is time base correction. Time base correctors (TBC) were developed principally to deal with imperfections in broadcast quality video for television. The first correctors were mechanical, but more recent systems are electronic and use digital image storage[1]. The essence of the TBC is the re-alignment of horizontal scan lines to remove synchronisation and timing errors, caused principally by the mechanical imperfections of analog video recorders. Video cassette tape is particularly prone to stretch and skew of the tape, as well as velocity errors, as the tape is mechanically dragged across the read/write head. Such errors are manifest when, for broadcast systems, video signals from different sources are mixed or title information is injected into the video signal. The phase lock loop (PLL) synchronisation used in most video equipment can correct for slowly changing phase of the video signal, but is not capable of correcting for rapidly varying phase changes.

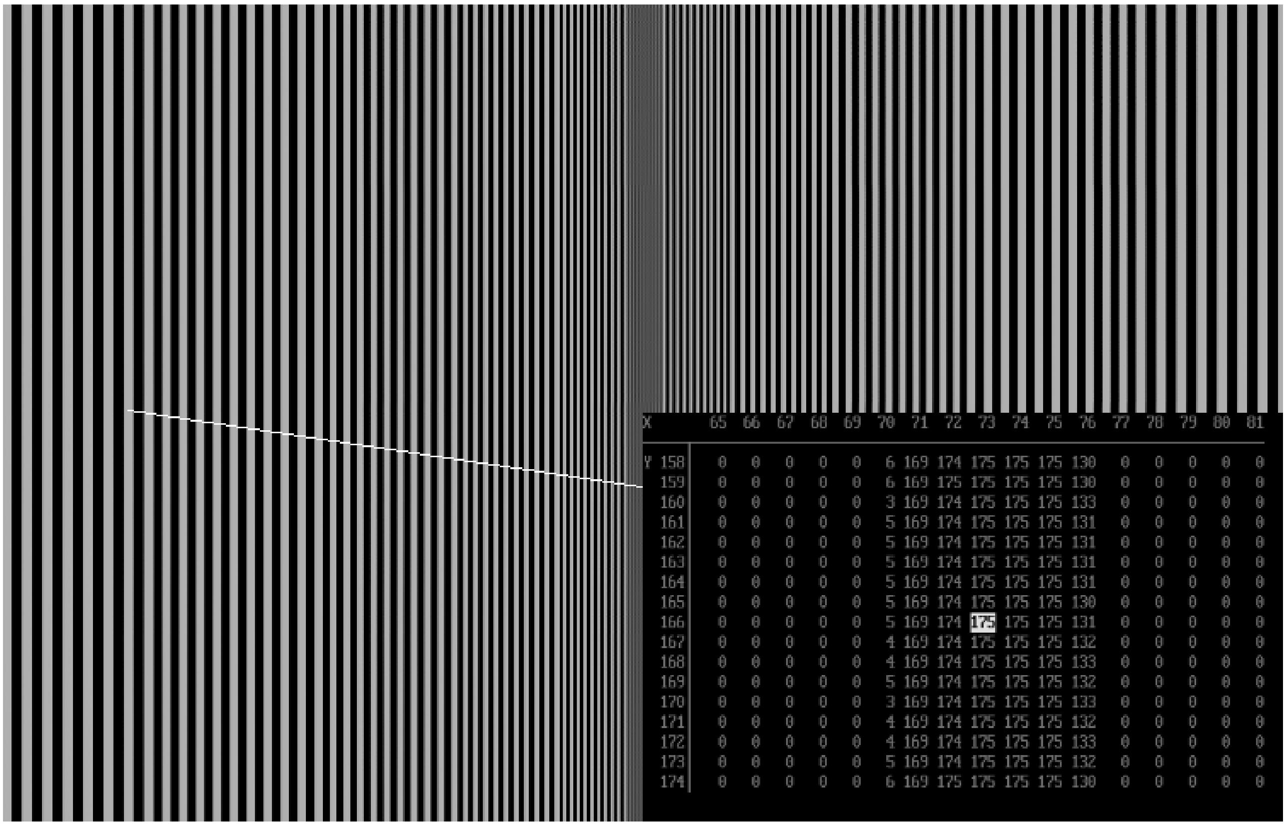
The current level of technology for TBCs specifies a window of approximately 15 scan lines in the video image and an accuracy of 15 nanoseconds. The window is scanned through the video frame, restoring the interval between horizontal synchronisation signals to accord with an external or internal standard. The window size is set by how quickly the TBC can correct the synchronisation and timing at frame rate. A larger window will produce a more consistent result, but requires very rapid processing. The 15 nanosecond accuracy corresponds to ±0.2 pixels for a CCD array with 752 horizontal pixels. The expectation for the TBC is that it should correct for horizontal scan line jitter and timing errors to this level of accuracy, but due to the windowing it will have a smoothing effect through the frame, rather than correcting the entire fame as a block.

Whilst time base correction may assist with synchronisation and time base errors, it will not restore the loss of integrity in video imagery caused by resampling and accumulation of noise. Even in the most controlled conditions, the loss of quality is inevitable for video images which are repeatedly recorded and re-recorded. The testing of the accuracy and repeatability of measurement using CCD cameras will certainly be affected by this loss in quality due to the smearing of, and increased noise in, the images.

3. TESTING WITH ARTIFICIAL LINE IMAGES

To initially verify the expected effects of analog recording and time base correction, a series of experiments were carried out using an artificial image created using a digital video generator. The image, shown in Figure 4, consists of a symmetric array of vertical lines. A small section of the image is shown at the lower right of Figure 4 in terms of grey values, and it is clear that the generator produces a near perfect line image, with zero background and peak grey levels of 175.

Nine cases of acquisition and analysis of CCD images are shown in Table 1. Case 1 is direct acquisition by a frame grabber as a best case scenario, against which all other cases will be compared. The remaining eight cases shown in Table 1 represent a comprehensive range of analog recording strategies which might be used in practice. Cases 2 and 4 are simple recording to and play back from video tape and disk respectively. Cases 3 and 5 introduce a TBC between the analog recording and the frame grab (see Figure 2) to electronically restore the synchronisation of the video signal. Case 7 introduces the possible option of an initial recording on video tape, followed by a transfer to video disk, to take advantage of the random access facility supplied by video disk technology. Case 8 again introduces a TBC prior to acquisition by the frame grabber. In both cases 7 and 8, a TBC is used in the link between the VCR and the video disk. Finally, cases 6 and 9 introduce frame averaging as an alternative to the TBC for the minimisation of synchronisation errors. In these cases the image is transmitted eight times and averaged by the frame grabber.



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X        65   66   67   68   69   70   71   72   73   74   75   76   77   78   79   80   81

Y 158|    0    0    0    0    0    6  169  174  175  175  175  130    0    0    0    0    0
  159|    0    0    0    0    0    6  169  175  175  175  175  130    0    0    0    0    0
  160|    0    0    0    0    0    3  169  174  175  175  175  133    0    0    0    0    0
  161|    0    0    0    0    0    5  169  174  175  175  175  131    0    0    0    0    0
  162|    0    0    0    0    0    5  169  174  175  175  175  131    0    0    0    0    0
  163|    0    0    0    0    0    5  169  174  175  175  175  131    0    0    0    0    0
  164|    0    0    0    0    0    5  169  174  175  175  175  131    0    0    0    0    0
  165|    0    0    0    0    0    5  169  174  175  175  175  130    0    0    0    0    0
  166|    0    0    0    0    0    5  169  174  175  175  175  131    0    0    0    0    0
  167|    0    0    0    0    0    4  169  174  175  175  175  132    0    0    0    0    0
  168|    0    0    0    0    0    4  169  174  175  175  175  133    0    0    0    0    0
  169|    0    0    0    0    0    5  169  174  175  175  175  132    0    0    0    0    0
  170|    0    0    0    0    0    3  169  174  175  175  175  133    0    0    0    0    0
  171|    0    0    0    0    0    4  169  174  175  175  175  132    0    0    0    0    0
  172|    0    0    0    0    0    4  169  174  175  175  175  133    0    0    0    0    0
  173|    0    0    0    0    0    5  169  174  175  175  175  132    0    0    0    0    0
  174|    0    0    0    0    0    6  169  175  175  175  175  130    0    0    0    0    0
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Figure 4. Artificially generated test image and grey level values of a small window.

A classic line jitter detection analysis was the first test carried out for all cases except those using averaging. Line centroids were computed for symmetrical positions near the left and right extremes of the horizontal scan lines. The results of this test are shown in the series of graphs comprising Figures 5 and 6. The graphs in Figure 5 show the variation in position of the left hand vertical line. The horizontal axis is in the units of pixels, showing variation with respect to the mean position of the line. The vertical axis is in the units of horizontal scan lines. Graphs of the right hand vertical line (not shown) exhibit very similar characteristics, but in most cases with increased spread of variation. The graphs in Figure 6 show the difference in position (right-left) of the two vertical lines.

Figure 5 can be interpreted as the error in horizontal line synchronisation, wherein the deterioration due to the analog recording is clearly evident. Time base correction does not appear to improve the synchronisation, and in some cases the TBC increases the magnitude of the errors whilst producing a smoother variation. The TBC accuracy of ±0.2 pixels may be sufficient to provide an aesthetically pleasing broadcast image, but it is inadequate for metric applications where synchronisation errors below ±0.01 pixels would be preferable. Figure 6 can be interpreted as the time base (or scale) error in the horizontal scan lines. Again the effect of analog recording is clear, as is the influence of the TBC. In general, the limits of the variations shown in Figures 5 and 6 agree with the specified TBC accuracy of ±0.2 pixels. However, significant improvements are evident for the cases involving transfers from video tape to video disk. The reasons for this improvement are unclear.

Case	Sequence	Comment
1	Image-FG	Direct acquisition to the frame grabber (FG)
2	Image-VCR-FG	Simple recording on S-VHS tape
3	Image-VCR-TBC-FG	Case 2 with TBC re-synchronisation
4	Image-disk-FG	Simple recording on video disk
5	Image-disk-TBC-FG	Case 4 with TBC re-synchronisation
6	Image-disk$_8$-FG	Case 5 with TBC replaced by 8 frame averaging
7	Image-VCR-TBC-disk-FG	S-VHS recording and transfer to video disk
8	Image-VCR-TBC-disk-TBC-FG	Case 7 with TBC re-synchronisation
9	Image-VCR-TBC-disk$_8$-FG	Case 8 with TBC replaced by 8 frame averaging

Table 1. List of the cases investigated to analyse the effects of analog recording

4. TESTING WITH CALIBRATION RANGES

The test range set up shown in Figure 7 was used to verify the initial tests made with the artificially generated image. Using a combination of a plumb line and target plate calibration, the effects of the analog recording, time base correction and frame averaging can be detected and analysed. Each of the nine cases given in Table 1 were tested using the plumb lines and target plate. The equipment shown on the right in Figure 7 allows frames from the CCD camera (in this case a Hitachi KP-M1 camera with a 752 by 480 pixel sensor and a 12.5mm lens) to be simultaneously frame grabbed and recorded on video tape and video disk. Short sequences were recorded to tape and disk, whilst the set up was stable, to enable the averaging of eight images.

As an initial test, a window was defined around a typical target image from one of the CCD frames of the array on the target plate. For each of the cases defined in Table 1, again except for the cases using averaging, an oscilloscope trace was recorded (using the video output from the frame grabber) for the horizontal scan line which passed as closely as possible through the centre of the target image. The window was exactly in the same position for each case. The results are shown in the graphs comprising Figure 8. The horizontal and vertical axes of these graphs represent time and analog video signal respectively. The single pixel peak (70 nanoseconds wide) at the left of the graphs is an artificially generated signal showing a grey level of 255 to establish an unequivocal vertical scale and horizontal origin point for the traces.

The direct acquisition case shows a well defined target image with no apparent artefacts in the background signal either before or after the peak. The subsequent cases show a progressively degraded trace, with increased noise, smearing of the image, reduction in peak signal and synchronisation error all evident. A number of cases show indications of "ringing" of the target image, that is disturbances to the background level following the peak signal. Again it is apparent that time base correction has a significant effect on horizontal synchronisation. In the examples shown in Figure 8 the shifts are interpreted to be block shifts of the entire frame, caused by changes in the frame synchronisation. The block shifts have magnitudes of up to 4-5 pixels, effectively masking any small effects from line jitter.

The changes in the traces shown in Figure 8 simply reinforce the expectation that analog recording degrades the video signal. The smearing of the images is caused by accumulation of resampling noise and the imperfect mechanical processes of analog video recording and playback.

The inclusion of the TBC into the sequence of analog video transfer has two effects. The first is to cause a block shift of the image. A consistent shift is of little consequence for self calibration testing, as the shift can be readily compensated by a change of the principal point location within the frame. The second effect is to restore some symmetry to the target images. Both the video tape and video disk alone appear to introduce asymmetries to the pixel values across the target image, whereas the cases with time base correction are noticeably less biased. Any systematic variation in the locations of the centroids of the target images is certain to adversely affect the accuracy of video metrology.

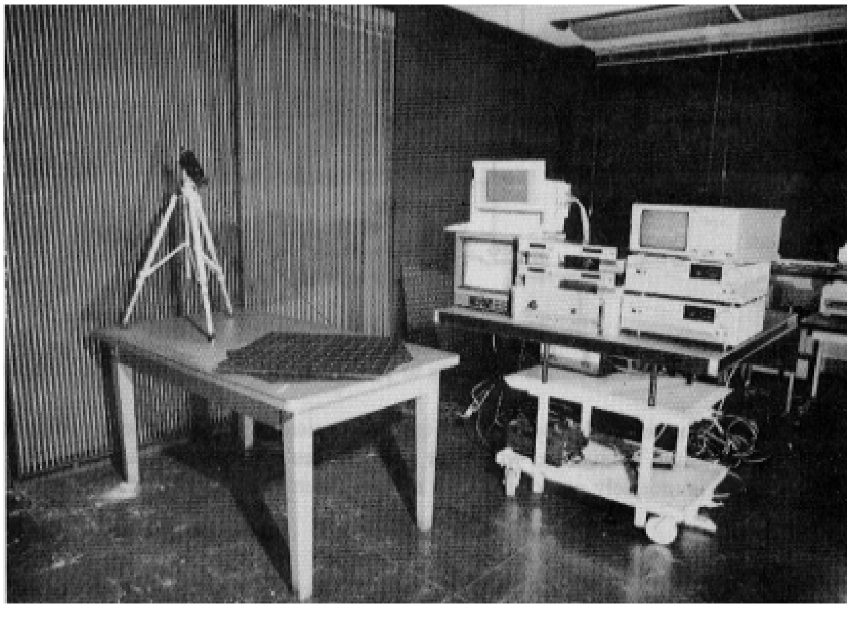


Figure 7. Set up used for the calibration range testing.

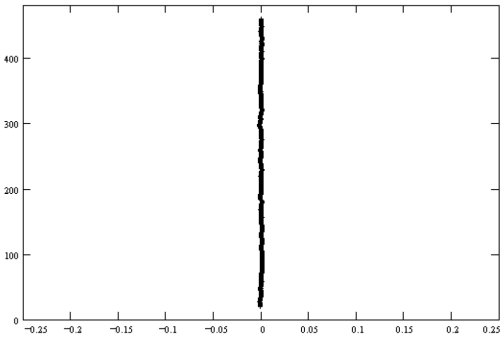


Image-FG

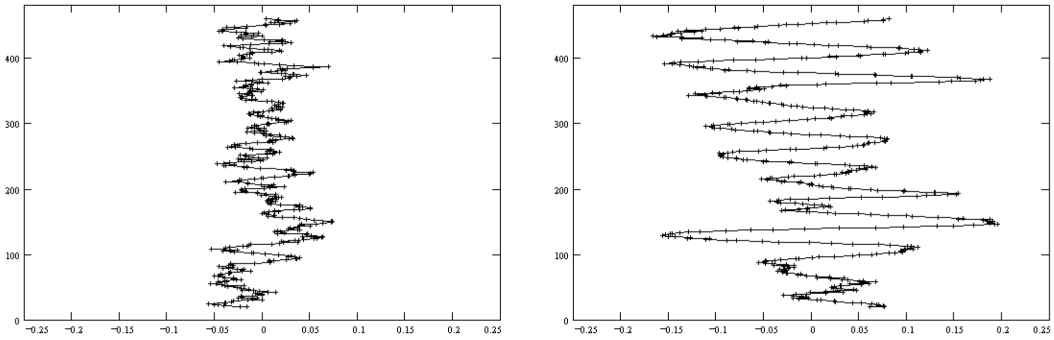


Image-VCR-FG Image-VCR-TBC-FG

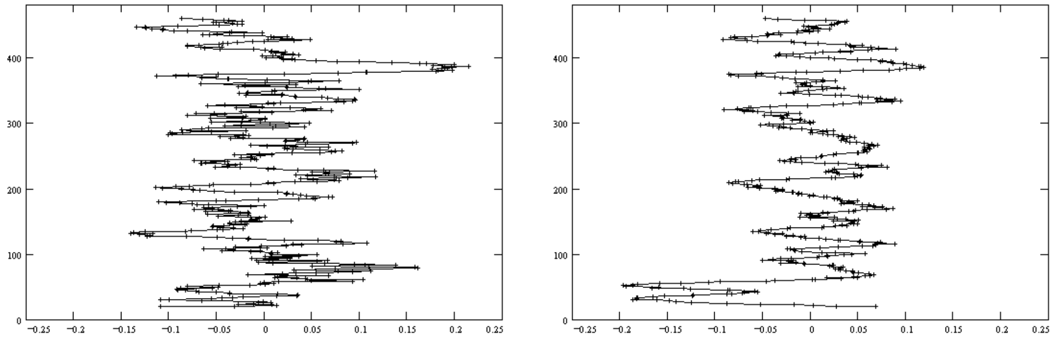


Image-disk-FG Image-disk-TBC-FG

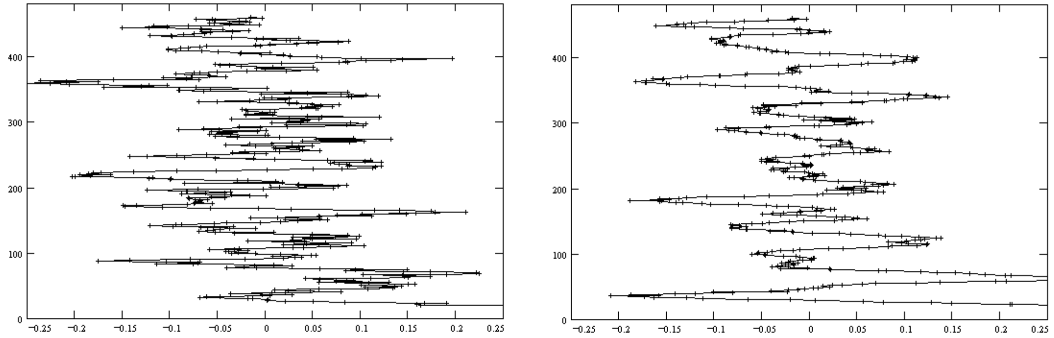


Image-VCR-TBC-disk-FG Image-VCR-TBC-disk-TBC-FG

Figure 5. Graphs of left line position in the artificially generated image for the seven cases.

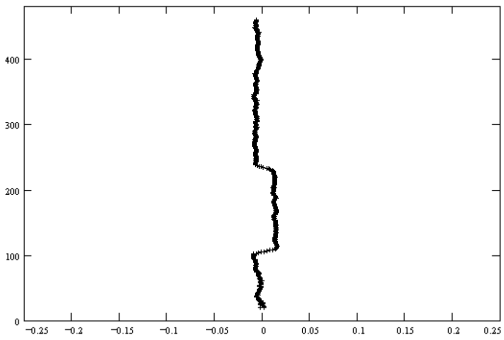


Image-FG

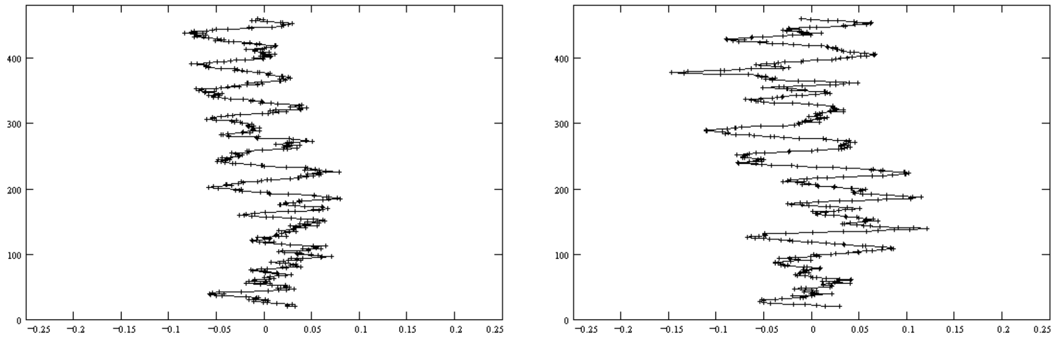


Image-VCR-FG

Image-VCR-TBC-FG

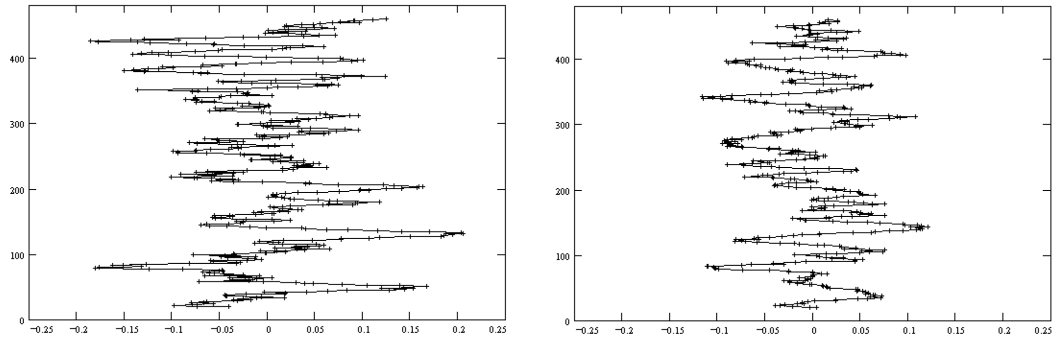


Image-disk-FG

Image-disk-TBC-FG

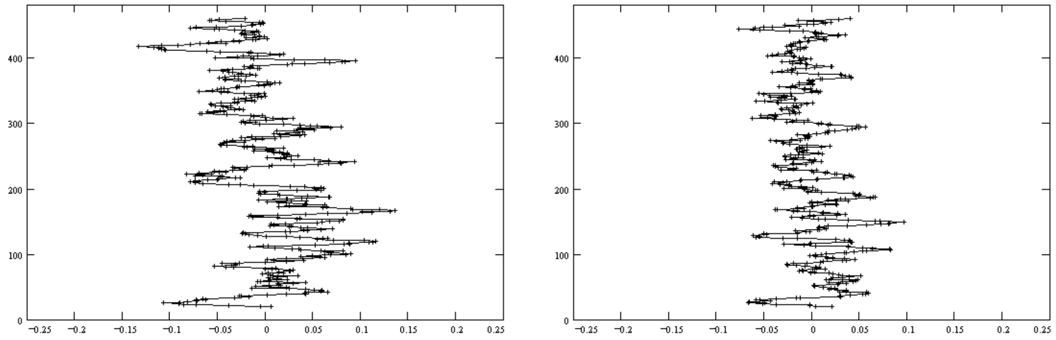


Image-VCR-TBC-disk-FG

Image-VCR-TBC-disk-TBC-FG

Figure 6. Graphs of the difference in position of the right and left lines in the artificially generated image for the seven cases.

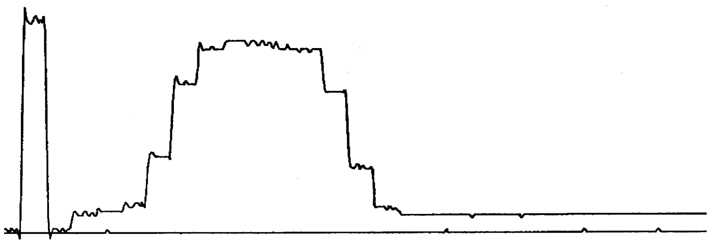
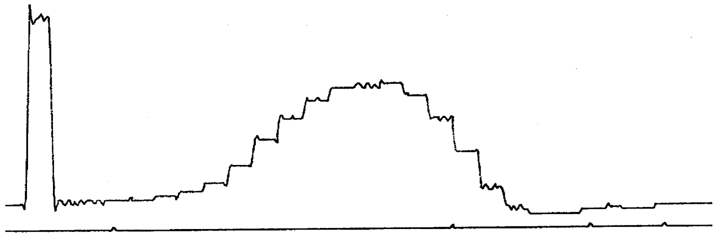


Image-FG


Image-VCR-FG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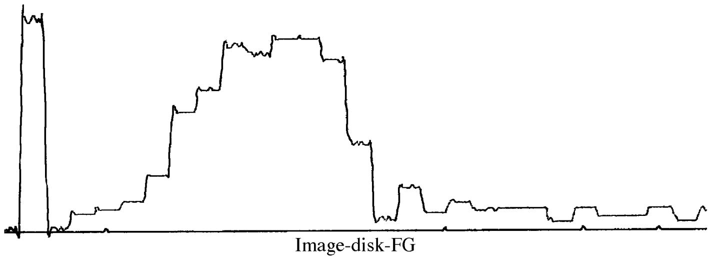
Image-disk-TBC-FG

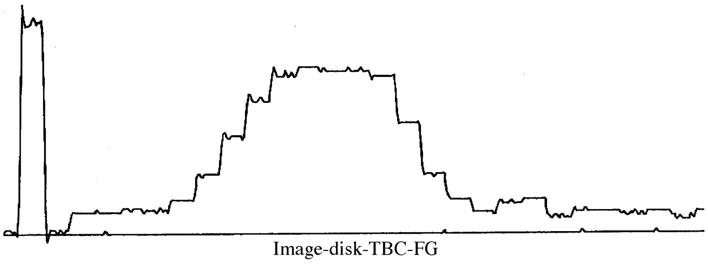
Image-disk-TBC-FG

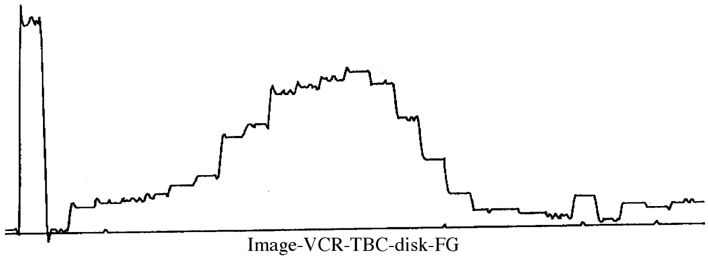
Image-VCR-TBC-disk-FG

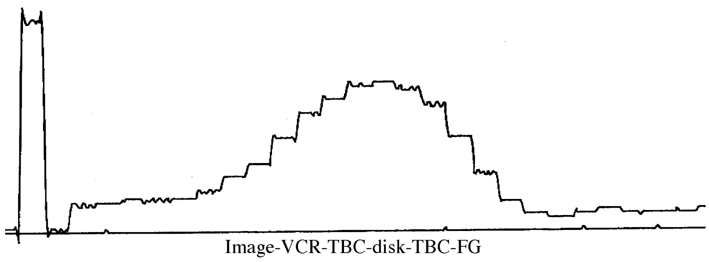
Image-VCR-TBC-disk-TBC-FG

Figure 8. Oscilloscope traces through the target image for the seven cases.

Having established that individual targets are affected by the video recording process, global testing using photogrammetric network analysis was carried out to verify the degradation. Two groups of results are shown in Table 2. The first group of results is from photogrammetric network adjustments with a fixed calibration for the Hitachi CCD camera. The second group of results is from self calibrating photogrammetric network adjustments with unconstrained calibration parameters. All network adjustments were computed from an eight station network of camera locations in a conical pattern around the target plate[6]. The convergence angle of diametrically opposed camera stations directed at the centre of the target plate was approximately 90°. The camera was rolled about the optical axis in order to minimise correlations between parameters in the network adjustment. The camera to object distance was adopted to maximise the coverage within the format of the sensor, without target image losses for any frame. The target plate has an array of 11 by 11 white, passive targets on a black background. Eight targets in the array were mounted on stand-off rods (not shown in Figure 7).

The parameters for the fixed calibration set were derived using a combination of a plumb line calibration[4,7] and a partly constrained self calibration using the target array. To compute a set of calibration parameters with optimum accuracy and independence, the lens distortions derived from the plumb line calibration can be used as constraints in the photogrammetric network. This strategy significantly improves the precision of the calibration parameters and increases the independence of all parameters in the self calibrating network adjustment.

Test Case	**Fixed** Calibration Parameters				**Free** Calibration Parameters			
	s_o	RMSE Image (micrometres)		RMSE Object (mils)	s_o	RMSE Image (micrometres)		RMSE Object (mils)
		x	y			x	y	
Image-FG	1.00	0.43	0.33	----	1.00	0.43	0.33	----
Image-VCR-FG	2.00	0.86	0.67	2.2	1.73	0.69	0.65	2.1
Image-VCR-TBC-FG	2.96	1.38	0.84	3.4	2.65	1.25	0.73	2.9
Image-disk-FG	1.96	0.93	0.51	2.0	1.78	0.82	0.51	2.0
Image-disk-TBC-FG	2.32	1.10	0.61	2.6	2.04	0.93	0.60	2.3
Image-disk$_8$-FG	1.87	0.91	0.47	1.9	1.67	0.78	0.46	1.8
Image-VCR-TBC-disk-FG	2.87	1.33	0.82	3.0	2.67	1.25	0.76	2.8
Image-VCR-TBC-disk-TBC-FG	2.80	1.27	0.85	3.4	2.47	1.12	0.76	2.9
Image-VCR-TBC-disk$_8$-FG	2.70	1.24	0.79	2.8	2.43	1.13	0.70	2.6

Table 2. Results of photogrammetric network adjustments for the nine cases (s_o is unit weight precision).

In the case of the fixed calibration set, the majority of the systematic error and noise accumulation caused by the off-line processing will be manifest in the results of the photogrammetric network solutions. Some of the error from the recording media and analog video transmission will be absorbed by small corrections to the exterior orientations at the camera stations, but the remainder will inflate the unit weight precision and degrade the image space and object space accuracies. As previously mentioned, the figures of merit for the best case scenario are set by the direct acquisition from the CCD camera to the frame grabber, and it is clear from Table 1 that there is the expected degradation of the results. Using the unit weight precision as a global indicator of repeatability, each media used in the off-line processing worsens the precision by 100%. Again as could be expected, there is a strong correlation between the degradations visually apparent in Figures 5 and 6, and the worsening numerical results shown in Table 2.

The average object space precision of target coordinates derived from the direct acquisition case is 1.1 mils. The figures shown in the RMSE object column in Table 1 show the root mean square error of the target coordinates for each case, as compared to the direct acquisition case. The degradation in accuracy is approximately 100% for each recording step introduced into the acquisition sequence.

Time base correction tends to worsen the results. The accuracy of ±0.2 pixels for the TBC corresponds to 2.5 micrometres in the image space, therefore it can be concluded that the TBC is simply not sufficiently accurate to adjust for the synchronisation or time base errors. In contrast, frame averaging does improve the results. The improvement in the signal to noise ratio produces marginal decreases in the degradation caused by the off-line recording processes. Averaging is therefore a viable alternative to a TBC in this instance.

The results for the free or self calibrating network adjustments demonstrate the limited ability of the calibration parameters to model the systematic errors caused by off-line processing. An improvement in the results of the order of 5-10% is gained using unconstrained calibration parameters for principal point, principal distance, lens distortions plus orthogonality and affinity in the image space. In all but one case there were large shifts in the principal point location in the x-axis direction in the image space (parallel to the horizontal scan lines). The largest shift recorded was approximately four pixels, which concurs with a visual inspection of Figure 8.

No further significant improvement was realised by using high order polynomial terms for image deformations. The same essential trends are shown for the fixed and free calibration results, which suggests that the effects of the off-line processing are sufficiently random in nature to prevent any systematic modelling.

5. CONCLUSIONS

Off-line processing for CCD camera based metrology is currently unavoidable in some situations. To allow post-processing, the video images must be recorded at frame rate using a high capacity storage device such as video tape or video disk. The empirical and rigorous testing carried out here to quantify the level of error indicates a significant loss of integrity in image and object space, caused by a decrease in the quality of the imagery. The main factors in the degradation appear to be an increase in the magnitude and frequency of occurrence of line jitter, and a smearing of target images due to resampling and the mechanical processes of analog recording.

More investigation of these phenomena is required to develop techniques and methodologies of prevention and/or restoration of the loss of image integrity. Appropriate additional parameter sets averaging strategies may reduce the accuracy loss. A potential solution to the problem of line jitter is the injection of artificial vertical lines, used here to effectively detect the line jitter. More sophisticated time base correction would also be worthy of testing, but only if the accuracy level is improved to the order of 1 nanosecond.

However, in due course this problem will be solved by alternatives to analog video storage. Arrays of disks capable of storing images at frame rate are commercially available, and whilst storage is currently limited to tens of seconds, the capacities will increase due to advances in computer technology and image compression. In the future, such systems will be combined with truly digital video systems which do not use analog video for the transmission of images. Analog video may never be replaced for general purpose video broadcast systems, but scientific and industrial applications are rapidly approaching the limits of this technology.

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