

Stability of zoom and fixed lenses used with digital SLR cameras

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ABSTRACT

Consumer grade digital cameras are widely used for close range photogrammetric applications because of the convenience of digital images and the low cost of capture and reproduction. Since the introduction of digital cameras in the 1980s, there has been a strong divide between relatively inexpensive, low resolution, compact digital cameras, and relatively expensive, high resolution, professional digital cameras. In recent years, the improved affordability of SLR (Single Lens Reflex) style digital cameras has increased the use of this class of camera, to some degree displacing professional cameras. Digital cameras are quite often bundled with a consumer grade zoom lens that is designed for the quality of the image, rather than the geometric stability of the calibration. When these cameras are used for photogrammetric applications, it is common practice that a high quality, fixed focal length lens is purchased and used in preference to the zoom lens. Calibration tests were conducted on a range of different digital cameras, all within the SLR class, to ascertain the differences between zoom and fixed lenses when used with these cameras. Analyses are presented that indicate the differences between the two lens types in terms of accuracy, precision and stability and suggest that although acceptable results can be obtained using zoom lenses, a fixed lens provides superior results.

BIOGRAPHY

Chris Bellman is senior lecturer and Director of Academic Programs in the School of Mathematical and Geospatial Sciences at RMIT University in Melbourne. He has a strong interest in digital photogrammetry, GIS and remote sensing applications and a particular interest in feature extraction from aerial photography.

He has been an active member of the profession for many years, through the Institution of Surveyors (Australia), the Victorian Society for Photogrammetry and Remote Sensing, the Remote Sensing and Photogrammetry Association of Australasia (RSPAA) and now the Spatial Sciences Institute. Chris is particularly keen to enhance the professional standing of those who practice in the spatial sciences by promoting the strengths and skills of the profession to the broader community.

INTRODUCTION

It is generally accepted that zoom lenses are less stable than fixed focal length lenses (referred to in this paper as “fixed” lenses), due in part to the movement of optical components that enable the principal distance of the zoom lens to be changed. Cameras fitted with zoom lenses typically exhibit some undesirable characteristics for photogrammetric purposes and a lack of stability means that the variations cannot be accurately modelled. In film-based 35mm cameras, radial distortion was found to vary considerably over the range of principal distance and was particularly significant at shorter principal distances (Fryer, 1986). As a consequence, zoom lenses were seldom used for close-range applications in film-based photogrammetry that demanded accuracy and reliability (Fryer, 1996).

With the advent of digital sensors, the use of zoom lenses has become more prevalent, as they offer greater flexibility and are able to compensate for the limited size of digital sensors. The mass produced nature of these lenses and a manufacturing emphasis on picture quality rather than geometric properties can mean that the optical axis is not well aligned with the normal of the image plane in the camera. As a result, changes in principal distance may cause significant movements of the principal point and departures of the principal point from the point of symmetry. Wiley and Wong (1995) found that for CCD cameras fitted with zoom lenses, the interior orientation was not stable through changes in principal distance. The study also found some non-linear variations in radial distortion with changes in principal distance and significant changes in decentring distortion. The significant changes in the interior orientation were confirmed by Burner (1995), however this research showed many of these changes to be linear, relatively stable and therefore suitable for modelling through camera calibration.

Despite the limitations of zoom lenses, they can be adequately calibrated and exhibit many of the characteristics of a fixed focus lens, if a constant principal distance is maintained (Li and Lavest, 1996). Digital cameras with zoom lenses are often used for many low and medium accuracy measurement tasks (Fraser, 1998; Habib *et al.*, 2005)

While there have been many studies that have demonstrated the satisfactory calibration of systems fitted with zoom lenses (Wiley and Wong 1995; Burner 1995; Läbe and Förstner 2004) and many more studies on the accuracy and calibration of fixed lens digital camera systems (Shortis and Beyer, 1997; Shortis, *et al.*, 1995, 1998; Clarke *et al.*, 1998), there is little evidence of studies that compare the performance of fixed and zoom lenses in a similar measurement environment.

The work reported in this paper has been undertaken because the authors consider that there is a qualitative expectation that zoom lenses will perform poorly compared to fixed-focus lenses, however the amount of degradation in accuracy and precision occurring with zoom lenses has not been reliably quantified. In one recent test on surface reconstruction, a relatively cheap digital camera with a zoom lens performed at levels similar to that of a more expensive, high resolution digital camera fitted with a fixed lens (Chandler, 2005). The present study seeks to quantify the degree of performance degradation that can be expected when a zoom lens is used for digital photogrammetry.

METHOD

In order to assess the relative performance of zoom lenses and fixed-focus lenses used for digital close range photogrammetry, compilations of photogrammetric data from a range of cameras and lenses, and generated from several independent projects, have been assessed. The projects used to generate the data used in the present study were varied in nature, and arose from both intentional and unintentional activities in the interests of a comparative analysis of performance of zoom and fixed lenses. Initial data sets were associated with camera calibrations to assess baseline performance in routine application to the characterisation of solar concentrators (Johnston, 1999; Johnston and Shortis, 1997; Shortis and Johnston, 1996) and quality control of manufacturing in the shipbuilding industry (Johnson *et al.*, 2004). Later data sets were captured specifically to compare zoom and fixed lenses using similar calibration networks. The zoom lenses used were consumer grade lenses, some of which were packaged with the cameras and feature a polycarbonate mounting plate. The fixed lenses were generally of a higher quality, used metal mounting plates and were closer to what might be regarded as a “professional” lens.

RMIT	RMIT University
EA	Excelsia Accomplis
UCL	University College of London
MCM	MidCoast Metrology

Table 1. List of the organisations providing camera calibration data.

The four organisations providing cameras for the studies are identified in table 1. The abbreviations in column 1 are used throughout to identify different cameras of the same model. Information on the five different cameras, the associated calibration networks and the camera specifications are shown in tables 2 and 3. All five cameras are SLR body style and it is evident from the specifications that all five cameras have very similar sensor resolution and physical size. The significant difference between the cameras from the two manufacturers are the use of CCD versus CMOS sensors, but a comparison of the sensor characteristics is beyond the scope of this paper. It should be noted that whilst the body construction material was either metal or polycarbonate, all cameras had a metal mounting plate for the lens.

Owner	Camera(s)	Zoom Lens	Fixed Lens(es)	Number of Photos	Number of Targets
RMIT	Nikon D70	Nikkor 18-70mm	Nikkor 20mm	18	82
	Canon EOS300D	Canon 18-55mm	Canon 24mm, Sigma 20mm	20	82
	Canon EOS20D	Canon 17-85mm	Sigma 20mm	19	80
EA	Nikon D70	Nikkor 18-70mm	Tamron 17mm	24	77 or 93
UCL	Canon EOS300D	Canon 18-55mm	Canon 28mm	14 or 19	150
MCM	Nikon D100	Nikkor 24-85mm	Nikkor 20 and 24mm	25	330
	Nikon D1X	Nikkor 24-85mm	Nikkor 20 and 24mm	26	330

Table 2. Details of the cameras, lenses and calibration networks.

Camera	Sensor Resolution	Sensor Type	Pixel Spacing (microns)	Body
Canon EOS300D	3072 by 2048	Canon CMOS	7.4	Polycarbonate
Canon EOS20D	3504 by 2336	Canon CMOS	6.4	Magnesium alloy
Nikon D1X	3008 by 1960	Sony CCD	7.9	Magnesium alloy
Nikon D70	3008 by 2000	Sony CCD	7.8	Polycarbonate
Nikon D100	3008 by 2000	Sony CCD	7.8	Polycarbonate (metal chassis)

Table 3. Camera specifications.

All calibrations of the cameras used multi-station convergent networks of exposures of an array of retro-reflective targets. The zoom lenses were set and fixed (by tape) at their shortest focal length. In all except one case (UCL EOS300D zoom lens), the networks included multiple camera rolls. The MCM calibration networks have a very consistent two roll (0 and 90) strategy whereas most other calibration networks have a four roll (0, 90, 180, -90) strategy that is less consistent. In all but one case (EA networks with 93 targets) the target array was a purpose built fixture with a significant depth component which, along with the camera rolls, minimises correlations between camera calibration parameters and camera orientation parameters (Kenefick *et al.*, 1972). Figure 1 shows the fixtures or test fields used for the camera calibration networks. The calibration parameter set in each case was based on the standard physical model of the principal point, principal distance, radial distortion, decentering distortion and an affine scale correction. All camera calibration networks were computed using a network bundle adjustment (Vision Measurement System (VMS), v7.6; Geometric Software, 2005). This software offers the ability to calibrate the cameras with block invariant parameters, or photo invariant principal point locations with all other parameters carried as block invariant.

The ability to include photo invariant principal point parameters was developed initially to address the affect of gravity on the spring mounted CCD arrays of Kodak DCS400 series cameras when the camera is rolled (Shortis *et al.*, 1998). For these cameras, the movement of the CCD array can be accurately modelled as there is a direct connection between the physical movement of the sensor and the apparent motion of the principal point within the image space.

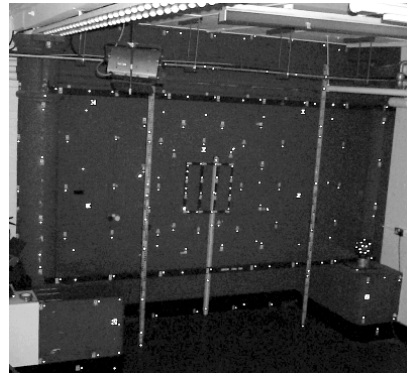
The photo invariant parameter approach was also adopted for the zoom lenses in the expectation that the effect of gravity on the lens during camera rolls would have a repeatable affect on the principal point location. However, in this testing it was expected that the weight of the lens may change the alignment of the optical axis with respect to the sensor array, rather than the sensor array moving with respect to the optical axis. The change in location during camera rolls may be a tilt effect of the relatively heavy zoom lens as a whole, or movement of the lens components within the lens barrel.

The use of a calibration parameter to effectively model a physical change in the optical path using the standard calibration model has a number of precedents. Fraser *et al.* (1996) found that the affine term in the standard camera calibration parameter set was strongly correlated with lenses rather than sensors (or cameras) in a calibration test that compared three lenses interchanged between two digital cameras. Harvey and Shortis (1998) described an underwater

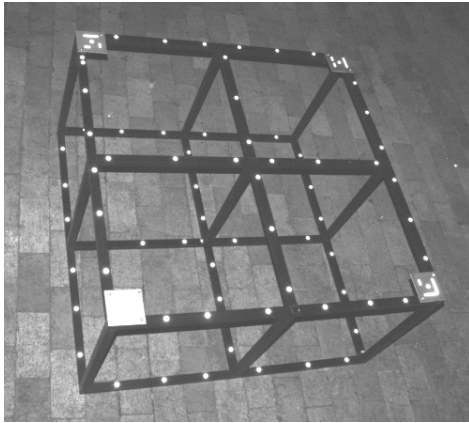
stereo-video system in which the standard calibration model is used to absorb the refractive effects of the air-acrylic-water interfaces with very consistent results, given a very stable relationship between the lens front surface and the camera port.



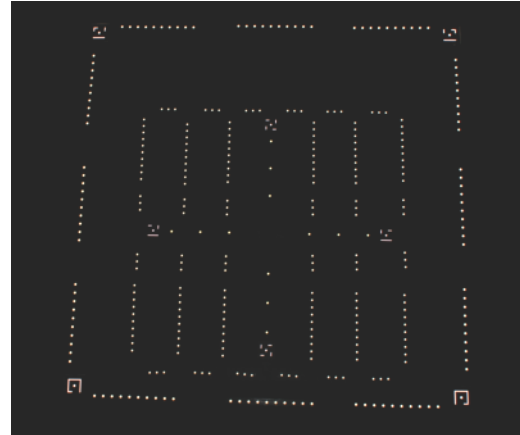
RMIT University



University College London



Excelsia Accomplis (77 targets)



MidCoast Metrology

Figure 1. Calibration fixtures or target arrays used by the four organisations. Three of the target arrays were of a similar size (1m x 1m x ~0.5m), while the University College London array was significantly larger (5m x 3m x 2m)

EXPERIMENTAL RESULTS

Results of the camera calibration networks with block invariant and photo invariant parameters are shown in tables 4 and 5 respectively. Within each table the corresponding zoom and fixed lenses on the same camera are shown in adjacent rows, as this is the primary focus of the analysis. The same sequence of calibrations is shown in each table so that the results for block and photo invariant calibrations can be compared as a secondary analysis.

The information shown in the tables provides measures of internal consistency and external accuracy. The RMS image residual from the networks is used to indicate the internal consistency of the calibration networks. Lesser magnitude values indicate better internal consistency in the network, which in turn indicates that the camera calibration is more stable. Unmodelled errors such as camera or lens instability will be manifest as larger RMS image residuals. This value is provided to indicate the general range of achievable target coordinate precisions for this class of digital camera. Also shown in the tables is the RMS error for known distances on scale bars included in the calibration networks for RMIT and MCM. The RMS error is effectively a measure of accuracy, because the distances are an independent check of the quality of the photogrammetric networks.

The target precision, shown as a proportional value to the maximum extent of the target array, is included in the tables to provide a measure of the external precision of the network.

Camera	Owner	Zoom or Fixed Lens	PD	RMS Image Residual		Target Precision	RMS Distance Error	Comments
			mm	um	1/pixels	1:	mm	
Nikon D70	EA	Nikkor 18-70	18.68	0.50	16	161000	-	93 targets, no distances
		Tamron 17	17.55	0.38	21	198000	-	
		Nikkor 18-70	18.92	0.48	16	89000	-	
		Tamron 17	17.55	0.32	24	122000	-	
	RMIT	Nikkor 18-70	18.48	0.76	10	60000	0.025	
		Nikkor 20	20.37	0.45	17	87000	0.029	
Nikon D100	MCM	Nikkor 24-85	24.80	0.46	17	71000	0.026	Averages of 2 sequential calibrations; Only two camera rolls
		Nikkor 20	20.40	0.23	34	110000	0.031	
		Nikkor 24	24.34	0.27	30	111000	0.025	
Nikon D1X	MCM	Nikkor 24-85	24.91	0.39	21	80000	0.027	Averages of 2 sequential calibrations; Only two camera rolls
		Nikkor 20	20.49	0.30	27	95000	0.029	
		Nikkor 24	24.44	0.26	30	109000	0.023	
Canon EOS 300D	UCL	Canon 17-85	25.35	0.39	19	74000	-	No distances; No camera rolls for the zoom lens and only two camera rolls for the fixed lens
		Sigma 28	28.50	0.50	15	64000	-	
	RMIT	Canon 18-55	18.55	1.09	7	45000	0.031	September 2004
		Canon 18-55	18.53	1.12	7	45000	0.041	October 2004
		Canon 24	24.38	0.39	21	99000	0.032	January 2005
		Canon 18-55	18.48	0.93	8	51000	0.046	
		Sigma 20	20.60	0.50	15	78000	0.042	
Canon EOS20D	RMIT	Canon 17-85	18.48	0.90	7	43000	0.066	January 2005
		Sigma 20	20.37	0.36	18	111000	0.026	

Table 4. Results for the calibration networks based on block invariant camera parameters.

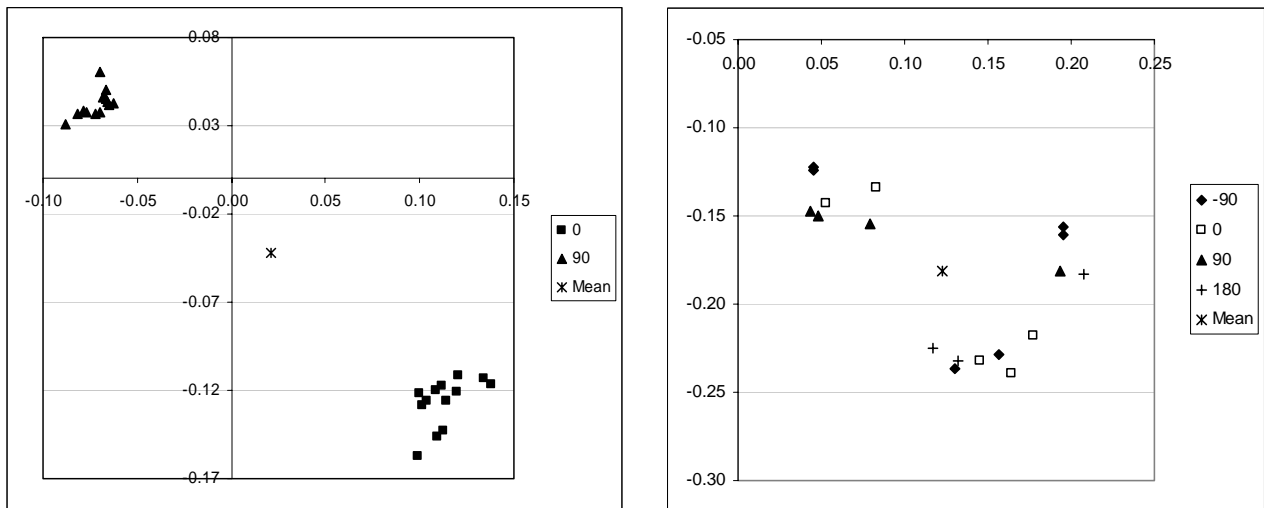


Figure 2. Inferred movement of the principal point for the MCM Nikon D100 with the Nikkor zoom lens (left graph) exhibiting a large span and distinct clustering with the two consistent camera roll angles. RMIT EOS300D with the Canon zoom lens (right graph) showing a similar span with a clustering pattern not clearly correlated with the four camera roll categories.

Not shown in the tables are the precisions of the principal point locations. In general the precisions of the location for block invariant calibrations were consistently of the order of 1-3 micrometres, whilst the precisions of the location for

photo invariant calibrations were more variable, but were of the order of 3-10 micrometres. This latter result is expected because the precision of parameters for a single exposure is always weaker than the precision of parameters that apply to all exposures. These values are necessary to assess the inferred movements of the principal point.

Camera	Owner	Zoom or Fixed Lens	PD	RMS Image Residual		Target Precision	RMS Distance Error	PP variation (mm)		Description of PP variation with camera roll
				um	1/ pixels			x	y	
Nikon D70	EA	Nikkor 18-70	18.68	0.45	17	155000	-	0.011	0.016	pseudo-random
		Tamron 17	17.55	0.36	22	184000	-	0.005	0.005	pseudo-random
		Nikkor 18-70	18.91	0.41	19	93000	-	0.023	0.015	non-roll clusters
		Tamron 17	17.54	0.31	25	114000	-	0.006	0.005	random
	RMIT	Nikkor 18-70	18.49	0.70	11	53000	0.020	0.017	0.010	pseudo-random
		Nikkor 20	20.36	0.41	19	81000	0.027	0.008	0.004	pseudo-random
Nikon D100	MCM	Nikkor 24-85	24.81	0.43	18	71500	0.027	0.095	0.084	distinct clusters
		Nikkor 20	20.41	0.20	39	118000	0.031	0.010	0.020	distinct clusters
		Nikkor 24	24.34	0.21	37	128500	0.014	0.021	0.012	distinct clusters
Nikon D1X	MCM	Nikkor 24-85	24.82	0.39	21	77500	0.028	0.103	0.077	distinct clusters
		Nikkor 20	20.51	0.24	34	111000	0.023	0.019	0.019	distinct clusters
		Nikkor 24	24.45	0.22	37	118000	0.023	0.014	0.007	distinct clusters
Canon EOS 300D	UCL	Canon 17-85	25.34	0.36	21	67000	-	0.011	0.003	n/a
		Sigma 28	28.48	0.49	15	52000	-	0.005	0.004	pseudo-clustered
	RMIT	Canon 18-55	18.48	0.79	9	49000	0.051	0.060	0.043	non-roll clusters
		Canon 18-55	18.53	0.86	9	48000	0.036	0.024	0.017	pseudo-random
		Canon 24	24.38	0.37	20	95000	0.033	0.006	0.006	pseudo-random
		Canon 18-55	18.45	0.79	9	50000	0.069	0.024	0.033	random
Sigma 20	20.61	0.41	18	75000	0.047	0.011	0.011	mostly random		
Canon EOS20D	RMIT	Canon 17-85	18.49	0.64	10	52000	0.132	0.098	0.089	non-roll clusters
		Sigma 20	20.36	0.34	19	96000	0.024	0.004	0.005	pseudo-clustered

Table 5. Results for the calibration networks based on photo invariant camera parameters.

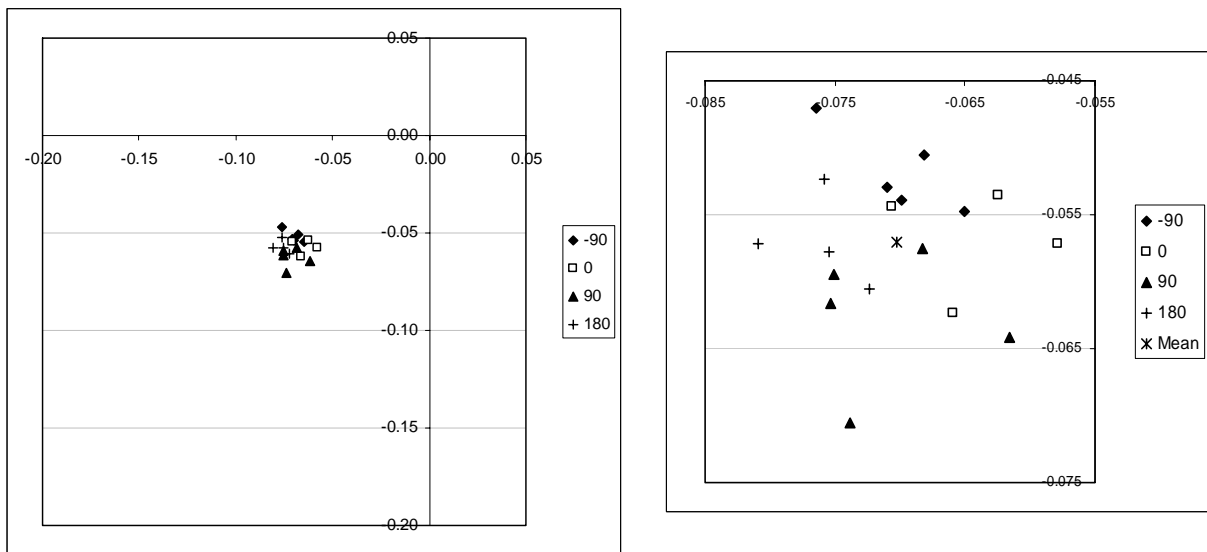


Figure 3. Inferred movement of the principal point for the RMIT Canon EOS300D with the Canon 24mm lens exhibiting a small span, generally random pattern but with some clustering for the four camera roll angles. Left graph

shown at the same scale as Figure 2 to allow a comparison, right graph shown at a much larger scale to display the structure.

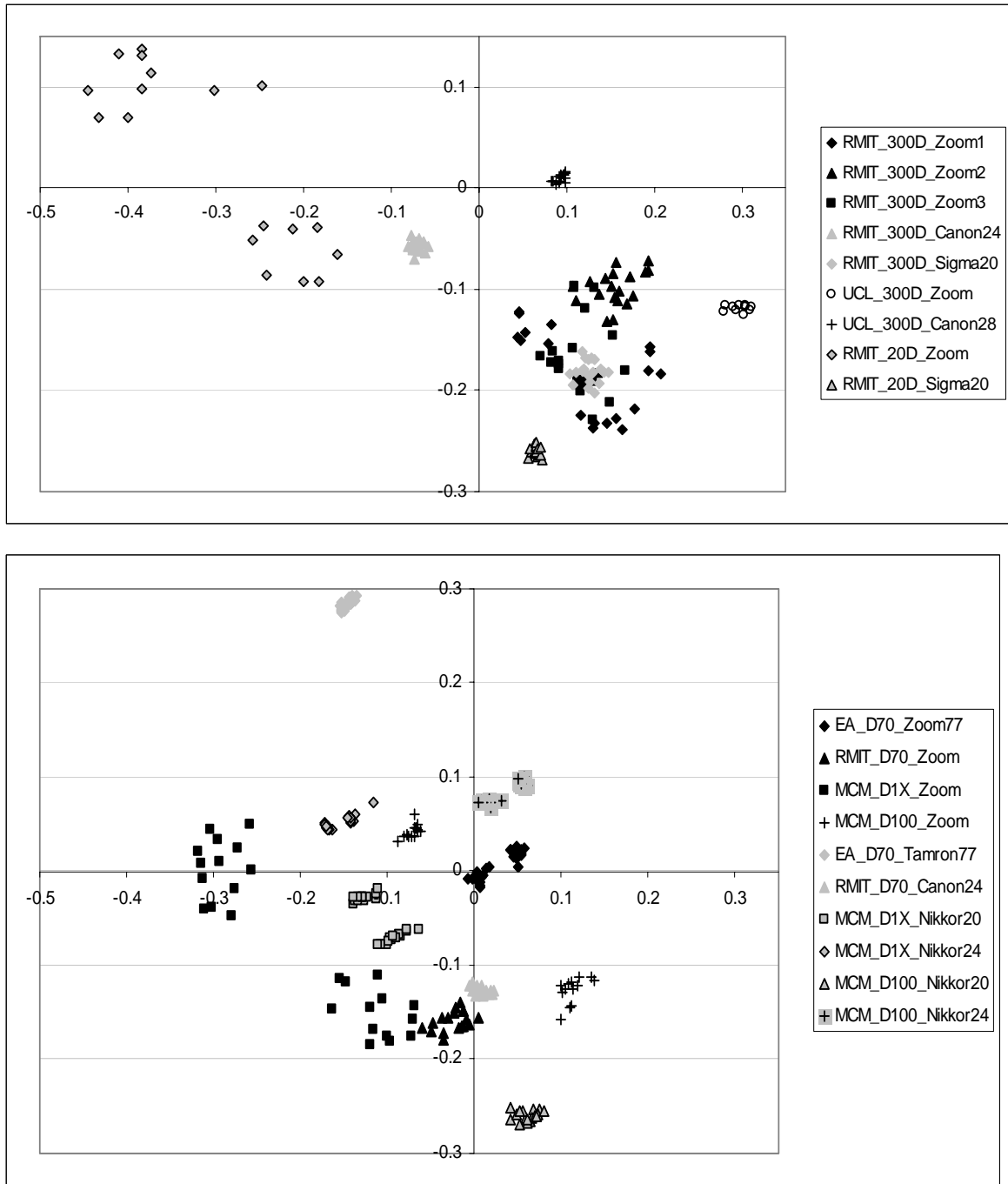


Figure 4. Inferred movement of the principal point for a selection of camera calibrations of the Canon (top graph) and Nikon (bottom graph) cameras showing the comparison between zoom and fixed lenses.

Figures 2 to 4 show the patterns of inferred movement of the principal point of the lenses of various camera and lens combinations extracted from the photo invariant calibration networks. Figures 2 and 3 give examples of specific

camera and lens combinations. Figure 4 gives an overview of the spread and patterns of zoom and fixed lenses. In Shortis *et al.* (1998) these patterns were used to demonstrate the estimated physical movement of the CCD sensor, whereas in this study the motion is used as an indicator of movement associated with the effect of gravity on the zoom lens as the camera is rolled, as well as other instabilities in the camera body and lens. A larger spread indicates greater instability. Clustering of principal point locations may indicate a consistent response to the same roll angle of the camera. Rather than include graphs for all camera and lens combinations test, a brief description of the patterns is given in table 5.

DISCUSSION

The results in the previous section clearly indicate the different quality of the networks produced by zoom lenses versus fixed lenses for the lenses and cameras used in this study. The primary indicator is the RMS image errors for the calibration networks. On average over all calibrations of all cameras, the calibration networks using zoom lenses have RMS image errors that are 72% larger than the calibration networks using fixed lenses. On average, there was marginal improvement of 6% for the results for calibrations using photo invariant parameters compared to the calibrations using block invariant parameters. These results indicate that the internal consistency of the networks for the zoom lenses is significantly less than that of the equivalent networks using fixed lenses, regardless of the calibration model.

A second comparison that can be made is that of the level of improvement of RMS image errors for the zoom and fixed lenses for calibrations with block invariant and photo invariant parameters. Assuming instability as a characteristic of zoom lenses, the expectation would be that the level of improvement for zoom lenses would be significantly greater because the photo invariant parameters would model some components of the instability of the lens. For fixed lenses there should be little if any improvement between the two types of parameter sets. The results only partly support these expectations. Comparing block invariant and photo invariant calibrations for zoom lenses shows an improvement of 13% in the RMS image error. This suggests that when the camera is rolled the movement of the lens as a whole, or elements within the lens, is being partially compensated by the use of photo invariant calibration parameters.

However the same comparison for fixed lenses shows an improvement of 12%, only marginally less than that of zoom lenses. It is clear from the results analysis above that fixed lenses are more stable than zoom lenses, yet the more complex camera calibration model produced no greater improvement for zoom lenses than for fixed lenses, indicating there is some other, unmodelled, influence on the system. One factor to consider is that there is some indication that this class of digital still camera may not be perfectly stable and some flexing of the non-rigid camera body or the lens mount might occur, even with a fixed lens. Another cause of instability might be movement of the internal components of the lens itself. Whilst not conclusive, further support for this instability is provided by significant changes in the principal point location between the sequential calibrations of the MCM cameras used with fixed lenses. The second factor is correlations between orientation parameters and calibration parameters. Shortis *et al.* (1998) noted that when using photo invariant calibration parameters, some improvement in the RMS image error is always manifest, even for extremely stable cameras, due to the interaction of correlations within the least squares estimation solution for the network. Therefore all of the testing is subject to a component of improvement that is not related to the stability, or lack thereof, of the camera, which may mask other effects.

The second indicator of differences in stability is the movement of the principal point based on the photo invariant camera calibration model. It is evident from figures 2-4 that the inferred motion of the principal point for the zoom lenses is, in general, much larger than the inferred motion of the principal point for the fixed lenses. The very large spread of principal point locations for the zoom lenses, significantly greater than the precision of locations of the principal point in all cases, demonstrates that the physical movement of the lens with the roll of the camera is a real phenomenon. In contrast, for the fixed lenses, the extent of the movement of the principal point is much lower, confirming that the improvement in the internal consistency of the networks based on photo invariant parameters is influenced by induced changes in correlated exterior orientation parameters.

The third and final indicator of stability is the variation in other camera calibration parameters between the calibrations with block invariant and photo invariant parameters. Whilst radial and decentring distortion values generally showed no significant changes, there were significant changes to the principal distance in some cases. A comparison of tables 4 and 5 demonstrates that variations in principal distance are associated with zoom lenses rather than fixed lenses. The mechanism for these changes is unclear and the changes may be an induced rather than a physical effect, but the higher magnitude values for zoom lenses could be an indicator of poorer stability.

A comparison of the RMS errors in distances for the calibration networks shows that, on average, the networks using cameras with the fixed lenses are 44% more accurate than the networks using cameras with the zoom lenses, and the improvement is consistent irrespective of block or photo invariant parameter sets. In contrast, a comparison between

calibrations with block and photo invariant calibration parameters for the cameras using zoom lenses shows an accuracy degradation of 11%. This indicates that, in general, the use of a photo-invariant calibration improves the internal consistency at the expense of external accuracy.

The influence of the polycarbonate versus metal camera body types (see table 3) can be estimated by comparisons of the RMIT EOS300D against the EOS20D and the MCM D100 against the D1X for comparable calibrations using the same fixed lens and block invariant calibration parameters. As could be expected, the two comparisons give quite different indications. Even allowing for the higher resolution of the sensor, the EOS20D produces significantly improved results for both internal precision (28%) and external accuracy (39%) when compared to the EOS300D. However, the D1X produces poorer results for internal precision (-13%) but improved results (7%) for external accuracy when compared to the D100. The introduction of photo-invariant parameters has little impact on the calibration results for the EOS20D, whereas there is an improvement in internal precision and a degradation of external accuracy for the EOS300D. Whilst this is a very limited sample, the magnesium alloy body of the EOS20D appears to provide greater stability than the polycarbonate body of the EOS300D. In contrast, the metal body and metal chassis of the D1X and D100 respectively lead to smaller and contradictory variations in the results.

SUMMARY AND CONCLUSIONS

The calibration of a number of different digital SLR cameras with both fixed and zoom lenses allows some general conclusions to be reached. First, when used with fixed lenses, the RMS image errors range from 1/15 to almost 1/40 of a pixel, corresponding to relative accuracies in the range of 1:50,000 to 1:130,000. Second, it is clear that there is a significant degradation of the internal consistency of the networks when the zoom lenses are used, resulting in RMS image errors as poor as 1/7 of a pixel. On average, there is a degradation in internal precision of 72% and, based on a more limited sample of distance checks, a degradation in external accuracy of 44%.

A plausible interpretation of the results of the camera calibrations is that the instability of the zoom lenses leads to significant changes in the calibration of the cameras. The introduction of photo invariant parameters, in this case the principal point location, realises only small improvements in the internal consistencies of the networks and degrades the accuracies of the networks. Because the instability is not recovered it is clear that the inclusion of only the principal point location in the photo invariant parameters is insufficient or that there is only a weak correlation between changes in the camera-lens relationship and the principal point location. The conclusion that must be reached is that the instabilities within the zoom lenses are not a simple movement in response to gravity, but rather a more complex process.

Calibration of the cameras with fixed lenses confirms previous research (Shortis *et al.*, 2001) that the camera body contributes to the lack of stability. Whilst this is not a surprising result given that none of the cameras have a rigid metal body nor are designed as metric cameras, it confirms that this lack of rigidity does reduce the potential of this class of camera for high accuracy applications, especially when used in conjunction with a zoom lens. Although the camera body instability limits the accuracy that can be achieved with these cameras, photogrammetric measurements achievable with professional digital SLR cameras in recent years are allowing significantly higher levels of accuracy than have been seen previously.

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