STABILITY OF ZOOM AND FIXED LENSES USED WITH DIGITAL SLR CAMERAS

M. R. Shortis[a], C. J. Bellman[a], S. Robson[b], G. J. Johnston[c] and G. W. Johnson[d]

[a]RMIT University, GPO Box 2476V, Melbourne 3001, Australia
[b]University College London, Gower Street, London WC1E 6BT, England
[c]Excelsia Accomplis, 31 Neilson St., Garran, ACT 2605, Australia
[d]MidCoast Metrology, PO Box 229, Bailey Island, Maine USA 04003

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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.

1. 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 fidelity 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), 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.

2. 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 (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. Consumer grade zoom lenses were used, 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.

Four organisations associated with the authors provided cameras for the calibration studies. Information on the five different cameras, the associated calibration networks and the camera specifications are shown in tables 1 and 2. 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.

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, decentring distortion and an affine scale correction. All camera calibration networks were computed using a network bundle adjustment which 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) describes 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.

3. EXPERIMENTAL RESULTS

Results of the camera calibration networks with block invariant and photo invariant parameters are shown in tables 3 and 4 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. Where available, also shown in the tables is the RMS error for known distances on scale bars included in the calibration networks. The RMS error is effectively a measure of accuracy, because the distances are an independent check of the quality of the 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. 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.

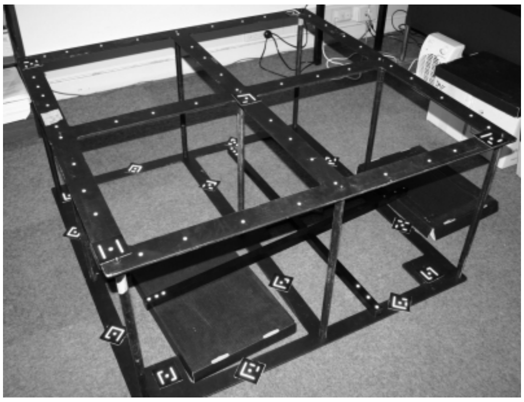
Figure 2 shows two typical examples of the patterns of inferred movement of the principal point of the lenses extracted from the photo invariant calibration networks. In Shortis *et al.* (1998) these patterns were used to demonstrate the estimated physical movement of the CCD sensor, whereas in this 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. Separate clusters of principal point locations may indicate a consistent response to the same roll angle of the camera.

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
Excelsia Accomplis (EA)	Nikon D70	Nikkor 18-70mm	Tamron 17mm	24	77 or 93
University College London (UCL)	Canon EOS300D	Canon 18-55mm	Canon 28mm	14 or 19	150
MidCoast Metrology	Nikon D100	Nikkor 24-85mm	Nikkor 20 and 24mm	25	330
(MCM)	Nikon D1X	Nikkor 24-85mm	Nikkor 20 and 24mm	26	330

Table 1. Details of the cameras, lenses and calibration networks.

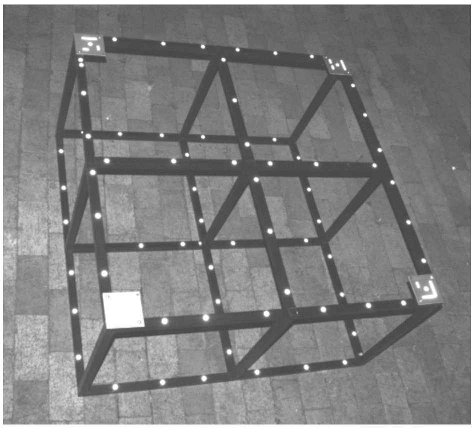
Camera	Sensor Resolution	Sensor Type	Pixel Spacing (microns)	Body
Canon EOS300D	3072 by 2048	Canon CMOS	7.4	Polycarbonate
Canon EOS20D	3504 by 2336	Canon CMOS	6.4	Magnesium alloy
Nikon D1X	3008 by 1960	Sony CCD	7.9	Magnesium alloy
Nikon D70	3008 by 2000	Sony CCD	7.8	Polycarbonate
Nikon D100	3008 by 2000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

Table 2. Camera specifications.

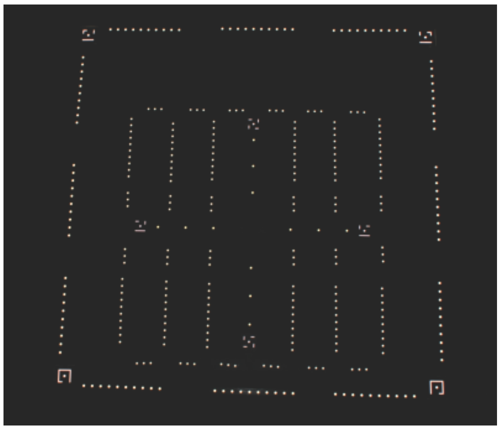


RMIT University

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)

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	-	77 targets, no distances
		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 (two) camera rolls for the zoom (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	
		Canon 18-55	18.48	0.93	8	51000	0.046	January 2005
		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 3. Results for the calibration networks based on block invariant camera parameters.

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

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

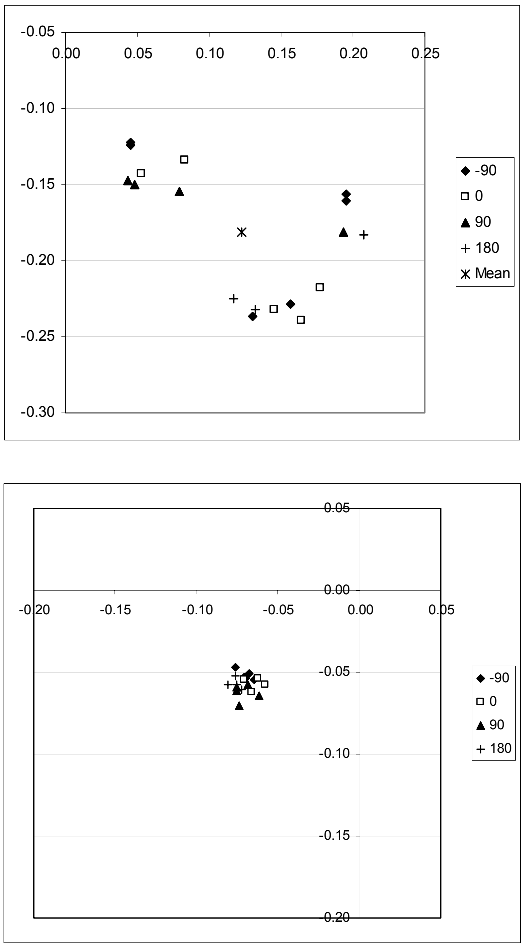


Figure 2. Inferred movement of the principal point for the RMIT EOS300D with the Canon zoom lens (top) and the Canon 24mm fixed lens (bottom).

4. 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 the level of improvement of RMS image errors when block invariant and photo invariant parameters are used in the calibration. Assuming zoom lenses are less stable, the expectation would be a significant level of improvement in RMS errors for zoom lenses when using photo invariant parameters, as these parameters should model some components of the instability of the lens. The better stability of fixed lenses should mean there is little or no improvement when photo invariant parameters are used. Comparing block invariant and photo invariant calibrations realises the same improvement (12-13% in the RMS image error), for both zoom and fixed 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 did not produce a greater improvement in RMS error for zoom lenses than for fixed lenses. This indicates that there is some other, unmodelled, influence on the system, such as the instability of the camera body, that is contributing to the error and masking any improvement provided by the more complex model.

In contrast, the movement of the principal point based on the photo invariant camera calibration model demonstrates clear differences in stability. It is evident from the principal point variations shown in table 4 and the example give in figure 2 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.

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 2) 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. 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.

5. 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%.

The results of the camera calibrations indicate that the instability of the zoom lenses leads to significant changes in the calibration of the cameras. The introduction of photo invariant parameters realises only small improvements in the internal consistencies of the networks and degrades the accuracies of the networks. 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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