New Advanced GNSS and 3D Spatial Techniques
18-20 February 2016, Trieste

Evaluation of 3D reconstruction accuracy in the case of stereo camera-pose configurations

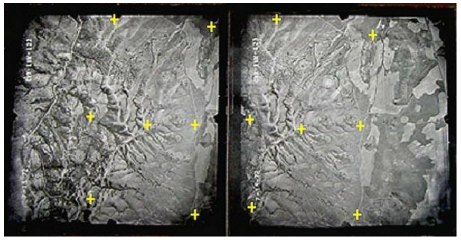
Xuan Zhang [a], Marco Scaioni [a,b], Gang Qiao [a]

[a] Tongji University, College of Surveying and Geo-Informatics, Shanghai, P.R. China
[b] Politecnico di Milano, Dept. of Architecture, Built environment and Construction Engineering (ABC), Milano, Italy

Summary

1. Motivations
2. Influence of camera calibration
3. Influence of geometric configuration
4. Discussion and conclusions

1.1 Motivations



- The stereo-pair is the basic configuration in Photogrammetry
- In traditional stereoscopic Photogrammetry (topographic applications):
  - important for stereo-plotting
- In modern Computer Vision Photogrammetry (for close-range, UAV applications):
  - important because of robot vision, dense matching (the most algorithms work on two images), 3D feature extraction, object recognition, stereo-sequence analysis, …
  - The concept of stereo-pair is more flexible, including slightly convergent images as well)

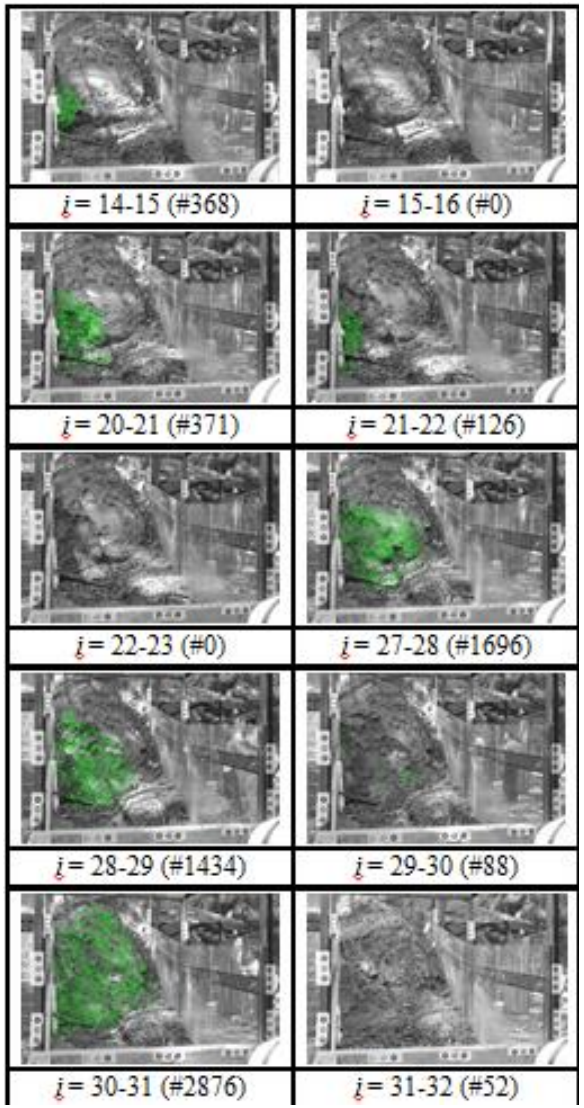
1.2 Motivations: Research interests

- Algorithms for computing relative orientation based on different parameterizations:
  - Physical parameters (perspective centre location, rotations)
  - Algebraic parameters (Fundamental/Essential matrices)
- Feature extraction
- Dense matching
- A priori evaluation of point 3D coordinate accuracy:
  - Theoretical methods (e.g., formulas based on the normal case)
  - Least-squares simulations

1.3 Motivations: Goals of this Study

- Today, in the era of Structure-from-Motion (SfM) Photogrammetry implemented in commercial SW packages, poor attention is paid to the evaluation of the accuracy of 3D points that can be computed from stereo-pairs
- The scope here is to analyze the effects of two factors that may have influence on 3D point determination:
  - Camera calibration
  - Geometric configuration (mainly relative convergence angle and baseline)
- The accuracy is also particularly relevant when stereo-pairs are used for high-precision measurements

1.4 Motivations: Example of high-precision photogrammetry



2.1 Camera Calibration: Background

- Any camera adopted in photogrammetric projects needs calibration:
  - Inner Orientation Parameters (c, x_0, y_0)
  - Additional Parameters (AP's) to correct geometric lens distortion
- Camera calibration can be pursued using consolidated models (e.g., Brown's model – *PE&RS*1970)

$$d\xi = (\xi - \xi_0)[k_1 r^2 + k_2 r^4 + k_3 r^6] + p_1[r^2 + 2(\xi - \xi_0)^2] + \\ + 2p_2(\xi - \xi_0)(\eta - \eta_0) + b_1(\xi - \xi_0) + b_2(\eta - \eta_0)$$

$$d\eta = (\eta - \eta_0)[k_1 r^2 + k_2 r^4 + k_3 r^6] + p_2[r^2 + 2(\eta - \eta_0)^2] + \\ + 2p_1(\xi - \xi_0)(\eta - \eta_0)$$

Radial symmetric distortion: k_1, k_2, k_3

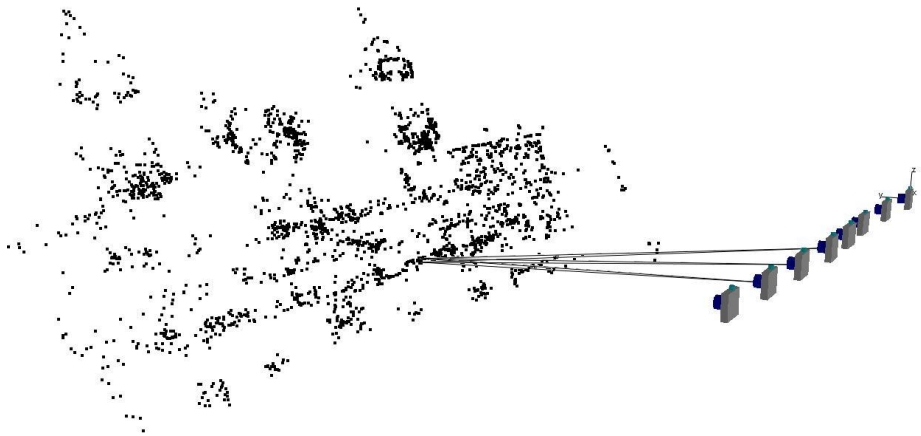
Decentering distortion: p_1, p_2

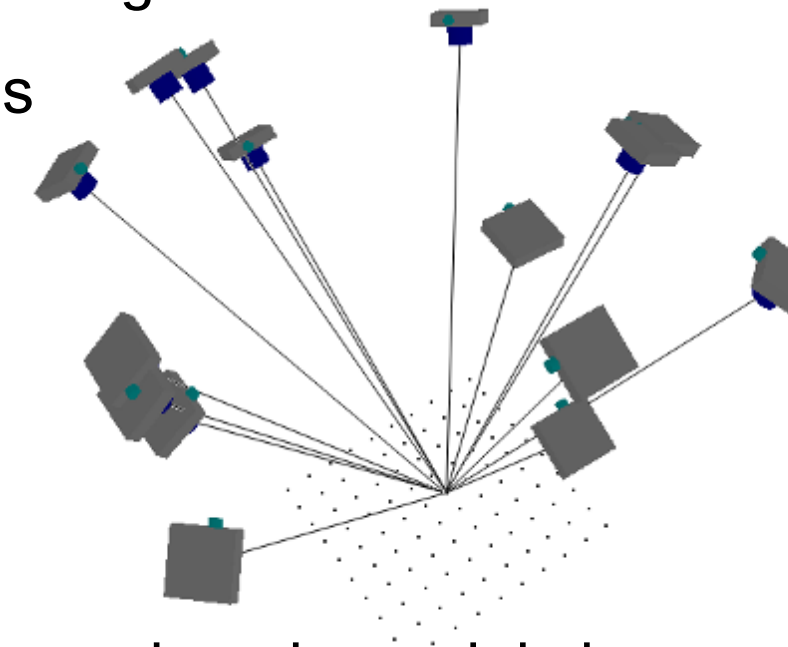
Affine distortion: b_1, b_2

- Methods:
  - Periodical offline calibration using a specific test field
  - Self-calibration during a photogrammetric project

2.2 Camera Calibration: The case of stereo-pairs

- In the case of stereo-pairs, cameras should be preferably calibrated offline because of the weak geometric configuration for estimating IO/AP's





- Calibration parameters are usually used as deterministic constants in photogrammetric projects
- The presence of errors might have a large impact in high-precision photogrammetry (e.g., in metrological applications)

2.3 Camera Calibration: Empirical test structure

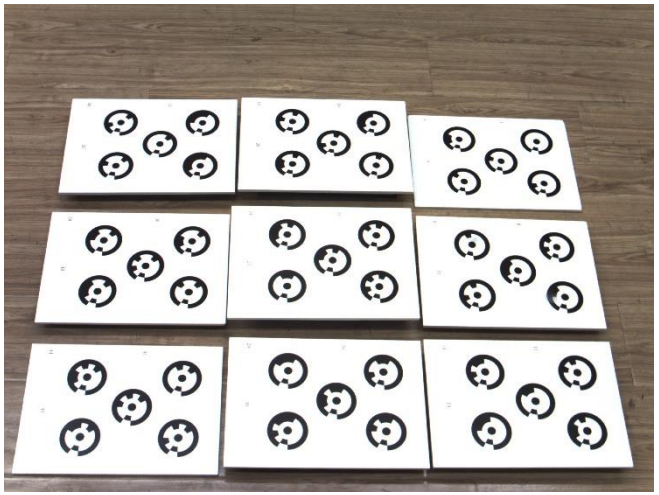
- Usually offline calibration is carried out once and periodically repeated (cameras might not be stable!)
- If there are anomalies in IO/AP's these will affect the determination of 3D points. How much?
- An empirical test has been set up to answer this question
  - repetition of the camera calibration procedure multiple times (here n=5) using a best practice technique
  - Check of results of any calibration (presence of correlations between IO/AP's/EO, statistical significance of estimated parameters)
  - Application of all estimated calibration parameter sets to the reconstruction of a set of control points (CP's) by using a stereo-pair
  - Analysis of results

2.4 Camera Calibration: Calibration procedure

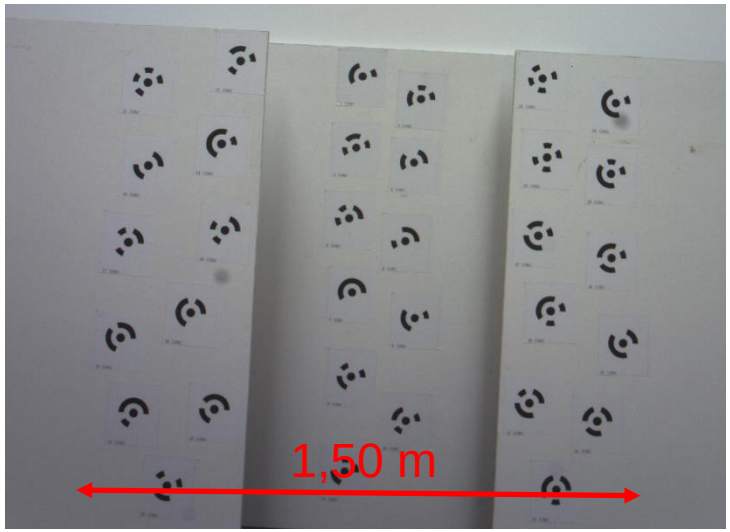
Adopted camera

Camera name	CGU2-500C
Camera type	industrial
Brand	CGimagetech
Sensor type	1/2.3 CMOS Coulor
Format size (pix)	2592*1944
Format size (mm)	6*4.5
Pixel size (μm)	2.3
Focal lens (mm)	8

Calibration field (Photomodeler coded targets)



3D check points



2.5 Camera Calibration: Calibration Results

	c [mm]	X_P [mm]	Y_P [mm]	K1	K2	P1	P2
1	8.69	2.94	2.43	1.61E-03	-3.11E-05	-6.00E-05	3.72E-05
2	8.70	2.96	2.44	1.60E-03	-3.34E-05	-5.45E-05	1.13E-04
3	8.71	2.96	2.44	1.58E-03	-2.68E-05	-5.46E-05	5.96E-05
4	8.71	2.96	2.44	1.60E-03	-3.16E-05	-5.67E-05	7.54E-05
5	8.70	2.96	2.44	1.63E-03	-3.30E-05	-5.42E-05	8.50E-05
Mean	8.70	2.95	2.44	1.61E-03	-3.12E-05	-5.60E-05	7.40E-05
Std	0.008	0.006	0.007	1.72E-05	2.34E-06	2.20E-06	2.53E-05
Largest Error	-0.013	-0.012	-0.014	2.70E-05	4.36E-06	-4.00E-06	3.89E-05
ID with Larget Error	1	1	1	5	3	1	2

2.6 Camera Calibration: Results on CP's

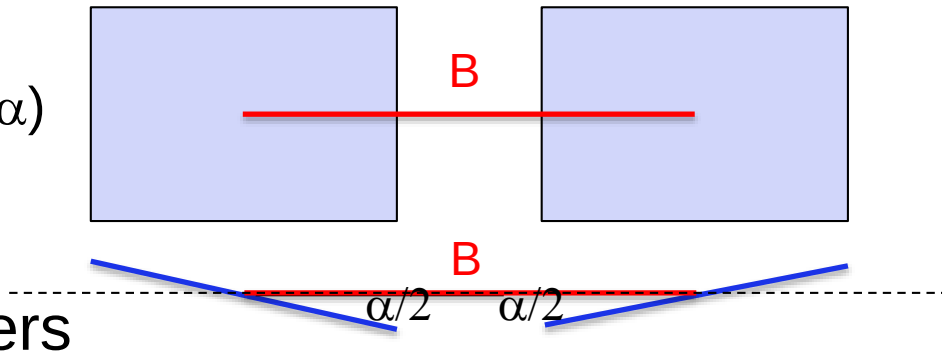
- A stereo-pair with B/Z=1/2,4 (B=1.5 m) was used in the normal case
- Image coordinate precision 1/3 pixel size
- Theoretical accuracies: σ_{xy}=±0.35 mm ; σ_z=±1.2 mm

change item	RMSE X [mm]	RMSE Y [mm]	RMSE Z [mm]	RMSE 3D [mm]
mean values	0.34	0.33	0.89	1.01
f	0.34	0.33	0.82	0.95
xy	0.37	0.35	0.85	0.99
k1	0.36	0.38	1.18	1.29
k2	0.37	0.41	1.33	1.44
p1	0.35	0.33	0.89	1.01
p2	0.38	0.34	0.89	1.03

- The effect of errors in radial distortion parameters are quite significant!
- Repeating the calibration can help improve the precision of camera calibration

3.1 Geometric configuration

- In this second step the effect of camera geometric configuration has been investigated
- Two relative orientation (RO) parameters have been explored since they are representative of most real cases:
  - Stereo-pair baseline (B)
  - Relative convergence angle (α)
- Application of 'mean' set of camera calibration parameters

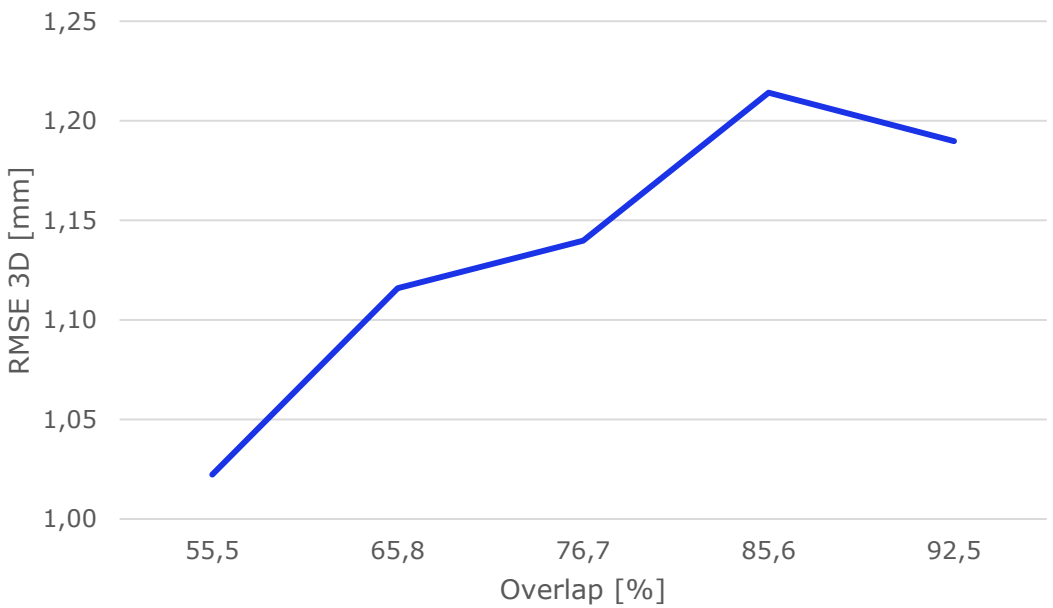


- Capturing stereo-pairs with varying RO parameters:
  - B : 4 values corresponding to overlaps 55% - 65% - 75% - 85 %
  - α : 4 values: 0° - 10° - 20° - 30 °

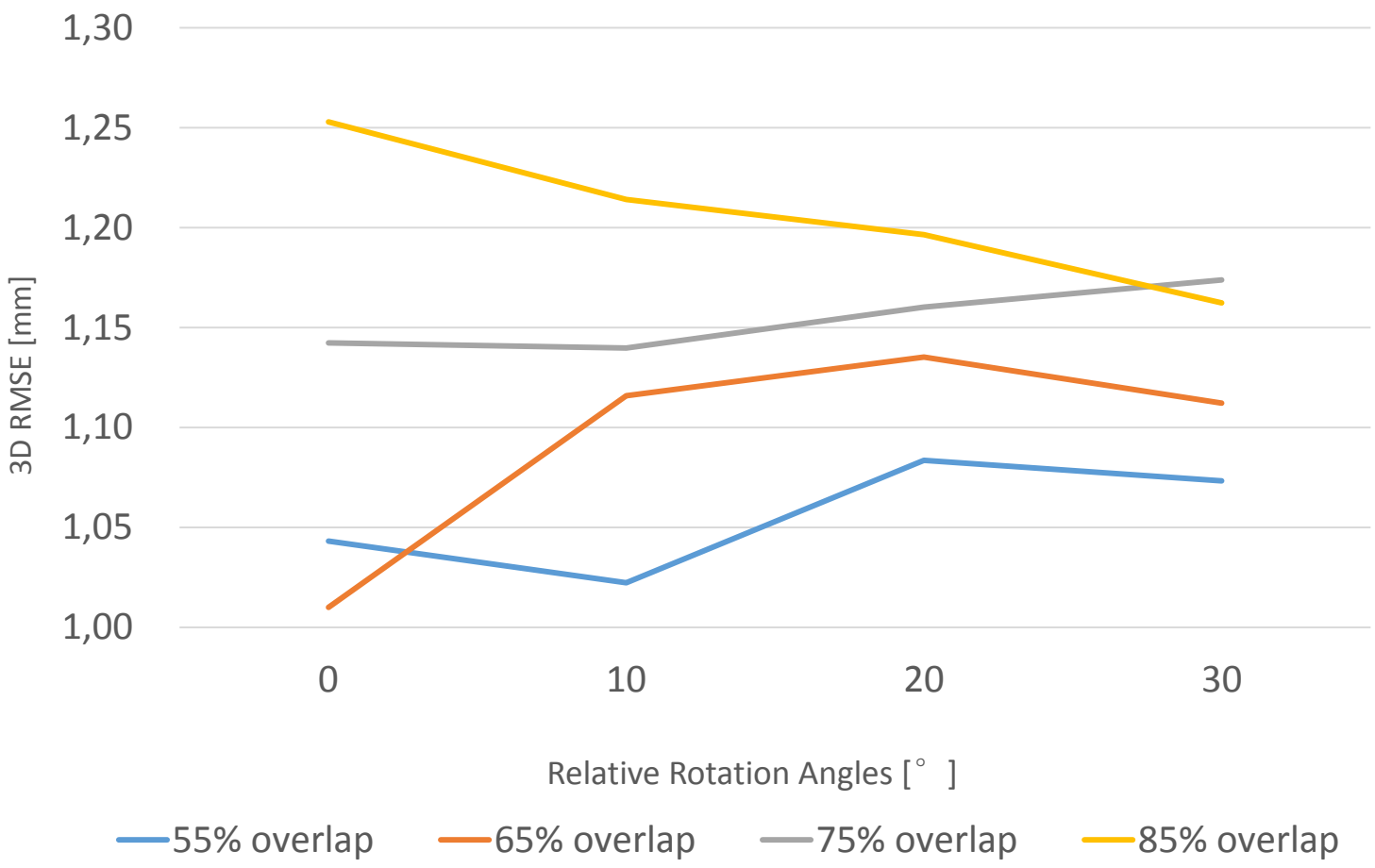
3.2 Geometric configuration: Example of one case

- Example with α=10° and varying Baseline/Overlap

ID	Overlap (%)	RMSE X [mm]	RMSE Y [mm]	RMSE Z [mm]	RMSE 3D [mm]
1	55.48	0.34	0.35	0.90	1.02
2	65.75	0.34	0.37	0.99	1.12
3	76.71	0.35	0.37	1.02	1.14
4	85.62	0.36	0.39	1.09	1.21
5	92.47	0.37	0.37	1.07	1.19

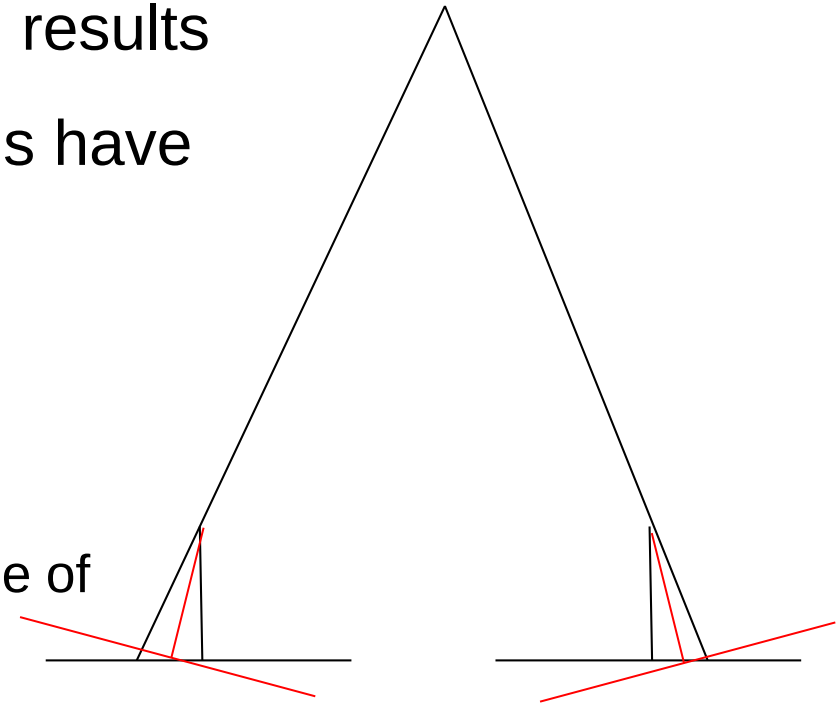


3.3 Geometric configuration: Review of all combinations



3.4 Geometric configuration: Simulations

- In order to compare the empirical results a set of Least-squares simulations have been operated
- Simulations depend on:
  - Geometry (well known)
  - Assumed point precision (in the case of image matching is affected by α)



- Simulations can be used only to check out the effect of varying baselines but not for angles (the intersection angle to object points are the same)

3.5 Geometric configuration: Real results *vs* Simulations

	Simulations			Real experiments		
overlap	RMSE XY [mm]	RMSE Z [mm]	RMSE 3D [mm]	RMSE XY [mm]	RMSE Z [mm]	RMSE 3D [mm]
55	0,32	1,49	1,56	0,33	0,93	1,04
65	0,34	1,67	1,74	0,34	0,89	1,01
75	0,36	1,91	1,97	0,35	1,03	1,14
85	0,39	2,23	2,30	0,38	1,14	1,26

- Results on the directions parallel to image planes are quite similar
- Results along depth are better in the real cases (from 0.3-0.4 times) -> presence of unmodelled correlations due to image matching

4.1 Discussion

- The effect of errors in camera calibration and the one due to geometric configuration (mainly baseline and relative convergence angle) have been investigated using a test field
- Results about calibration showed that biases in the estimation of radial distortion can be significant (0.1%)
  - This is almost important in the case of metrological applications
  - Less important when relative point displacement have to be detected in stereo-image sequence (if cameras are fixed)
- In the case of important/high-precision photogrammetric projects, calibration should be repeated (at least 3-5 times)

4.2 Discussion

- The length of baselines is influencing the results (up to 25% increase of RMSE)
- Convergence angles have less influence (10% times)
- The comparison with theoretical simulations shows that probably some unmodelled correlations between image points in the two images exist (matching might not be an independent process)
- Checking the accuracy of results by means of a test field is always very important in high-precision projects

4.3 Future work

- Extension of the experimental stage using more cameras, including also other camera types (SLR, small-format, large format, smartphone cameras, …)
- Analysis of other simple configurations (triplets in different configurations, 4-images, image sequences, block)
- Trying to investigate the effect of image matching when dealing with convergent images, and to analysis the presence of correlations (Master-Slave methods)

Thanks for your attention!

Acknowledgements:

- Prof. Raffaella Cefalo for organizing this meeting
- 863 National High-Tech R&D Programme of China (No.
- 2012AA121302),
- 973 National Basic Research Programme of China (No. 2013CB733203 and 2013CB733204)