

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

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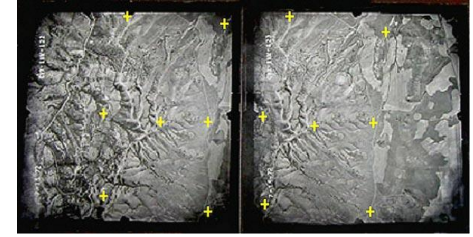
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1. Motivations
2. Influence of camera calibration
3. Influence of geometric configuration
4. Discussion and conclusions

## 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)

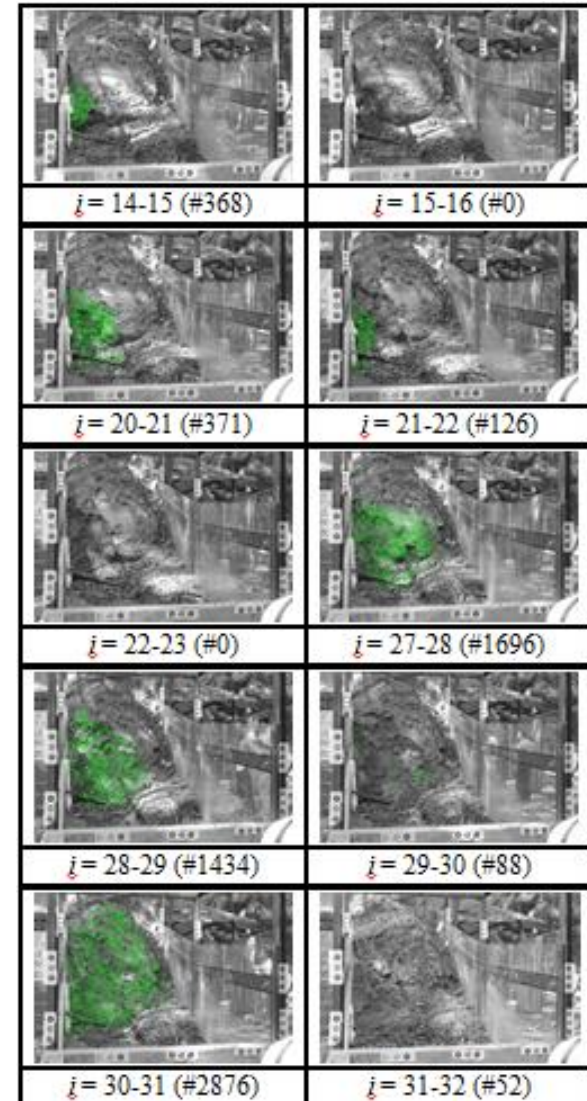
## 1.2 Motivations: Research interests

- ❑ 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&RS1970*)

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

Radial symmetric distortion:  $k_1, k_2, k_3$

Decentering distortion:  $p_1, p_2$

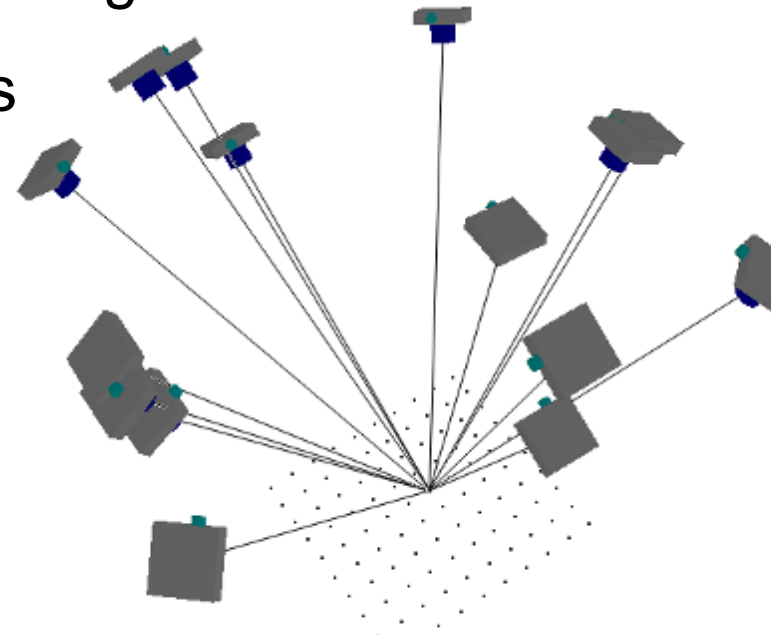
$$d\eta = (\eta - \eta_0)[k_1 r^2 + k_2 r^4 + k_3 r^6] + p_2[r^2 + 2(\eta - \eta_0)^2] + 2p_1(\xi - \xi_0)(\eta - \eta_0)$$

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

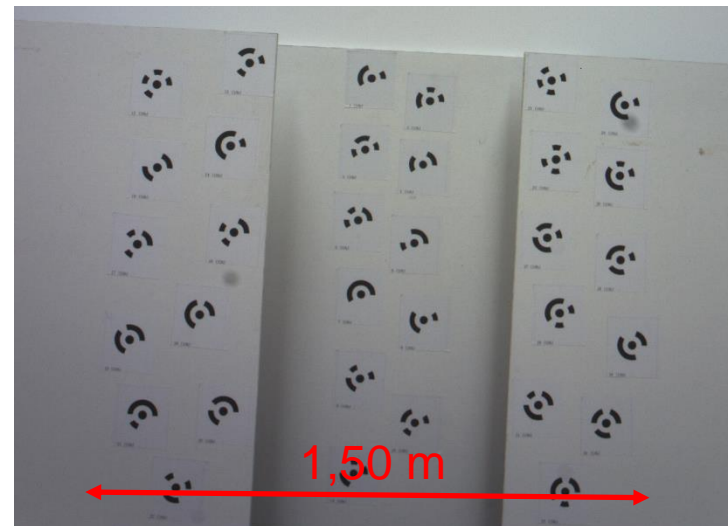
Camera name	CGU2-500C
Camera type	industrial
Brand	CGimagetech
Sensor type	1/2.3 CMOS Coulor
Format size (pix)	2592*1944
Format size (mm)	6*4.5
Pixel size ( $\mu\text{m}$ )	2.3
Focal lens (mm)	8



### Calibration field (Photomodeler coded targets)



### 3D check points



## 2.5 Camera Calibration: Calibration Results

	c [mm]	X <sub>p</sub> [mm]	Y <sub>p</sub> [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 Target Error	1	1	1	5	3	1	2

## 2.6 Camera Calibration: Results on CP's

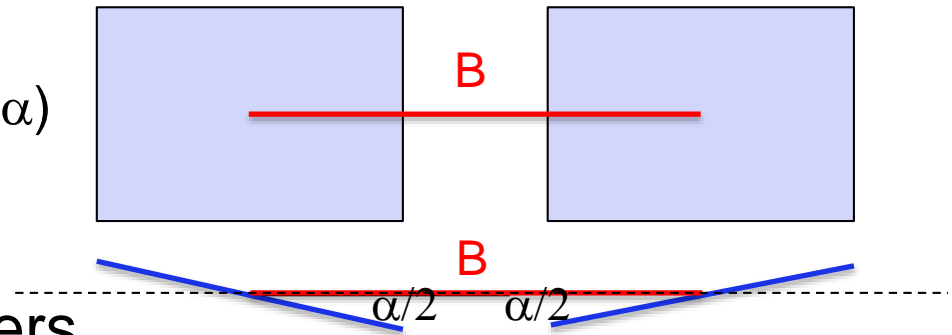
- ❑ A stereo-pair with  $B/Z=1/2,4$  ( $B=1.5$  m) was used in the normal case
- ❑ Image coordinate precision 1/3 pixel size
- ❑ Theoretical accuracies:  $\sigma_{xy}=\pm 0.35$  mm ;  $\sigma_z=\pm 1.2$  mm

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

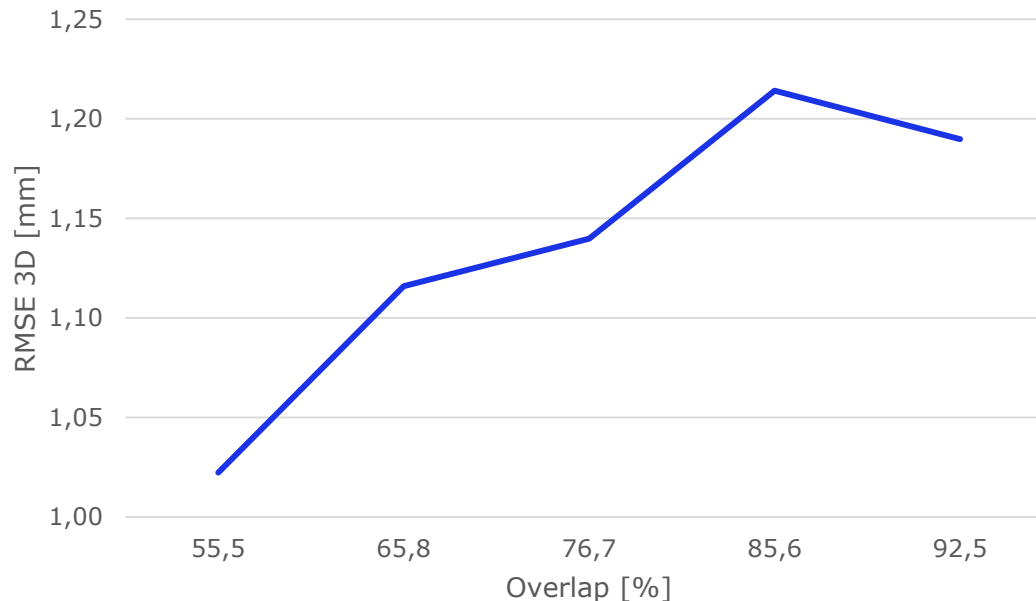
- ❑ In this second step the effect of camera geometric configuration has been investigated
- ❑ Two relative orientation (RO) parameters have been explored since they are representative of most real cases:
  - ❑ Stereo-pair baseline ( $B$ )
  - ❑ Relative convergence angle ( $\alpha$ )
- ❑ Application of 'mean' set of camera calibration parameters
- ❑ Capturing stereo-pairs with varying RO parameters:
  - ❑  $B$  : 4 values corresponding to overlaps 55% - 65% - 75% - 85 %
  - ❑  $\alpha$  : 4 values:  $0^\circ$  -  $10^\circ$  -  $20^\circ$  -  $30^\circ$



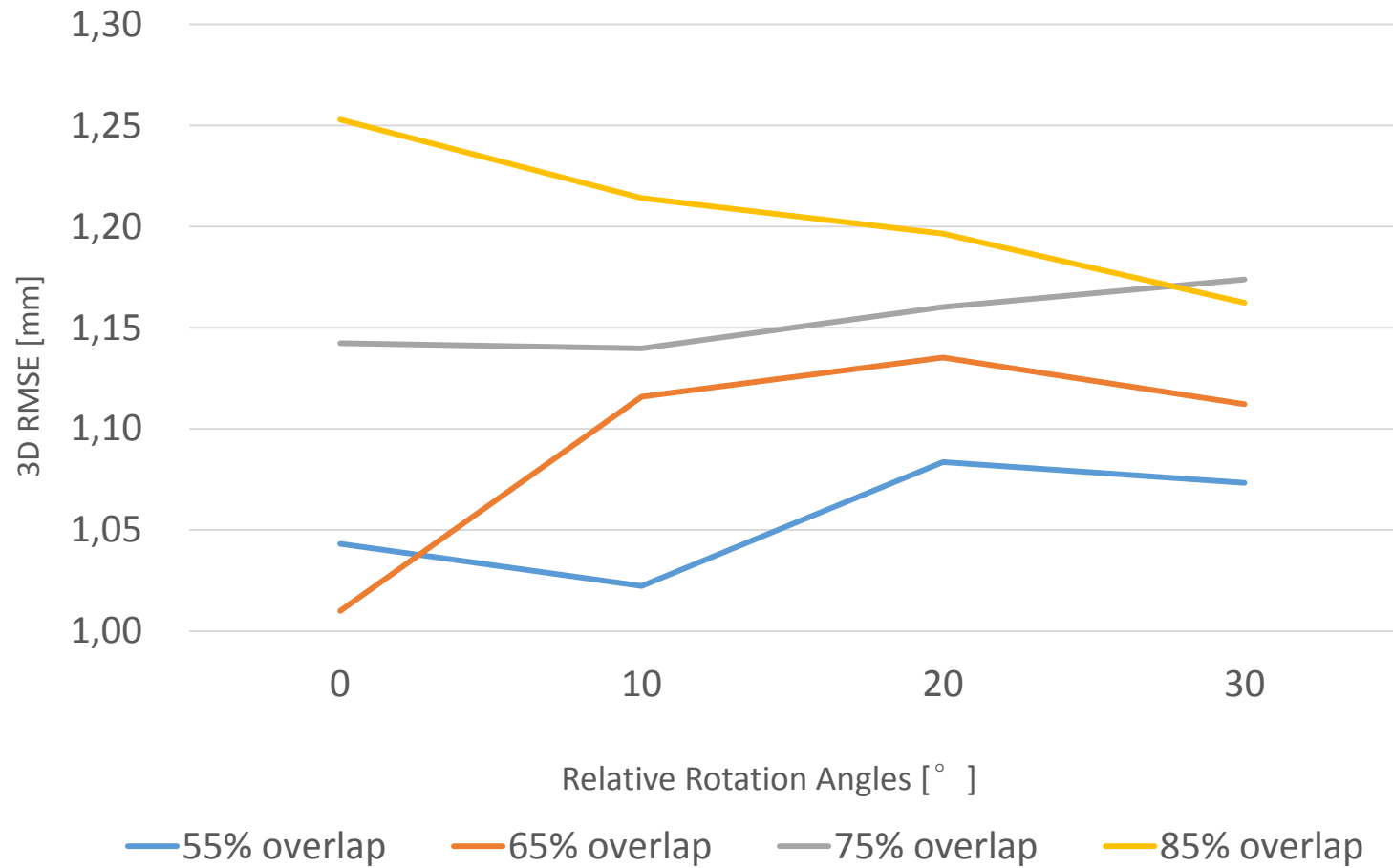
## 3.2 Geometric configuration: Example of one case

□ Example with  $\alpha=10^\circ$  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



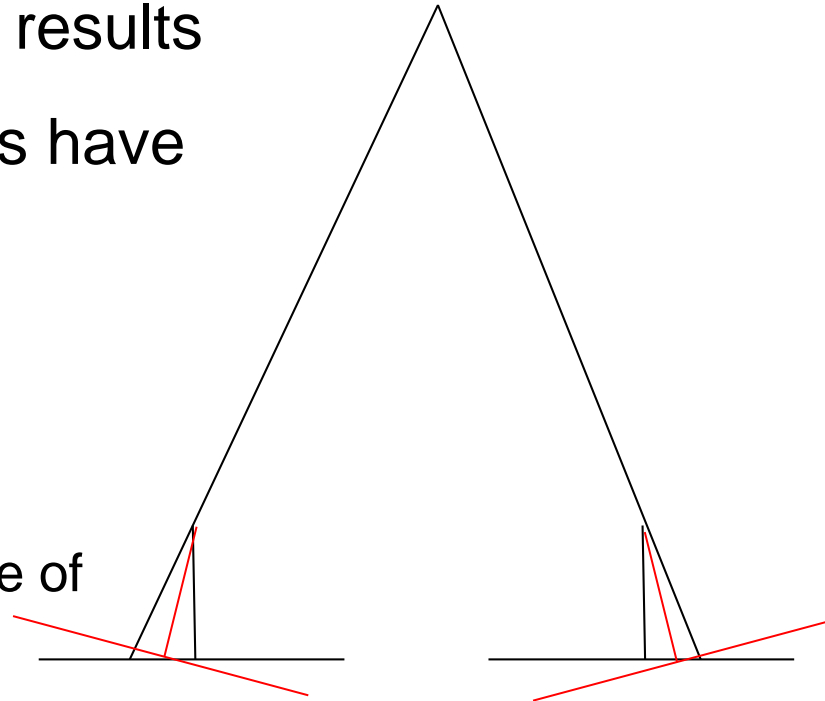
## 3.4 Geometric configuration: Simulations

- 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  $\alpha$ )



- 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!

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