Stability analysis of a multi-camera photogrammetric system used for structural health monitoring

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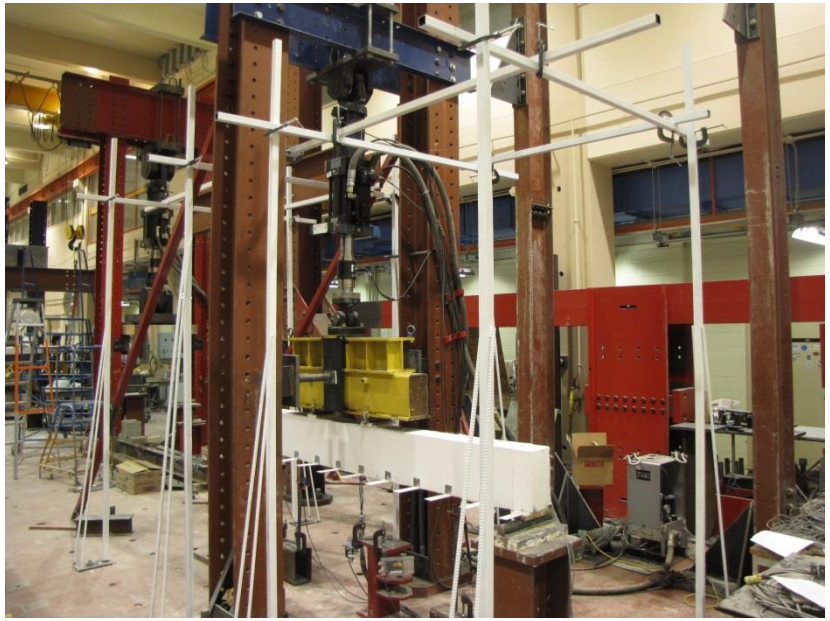
Structural health monitoring

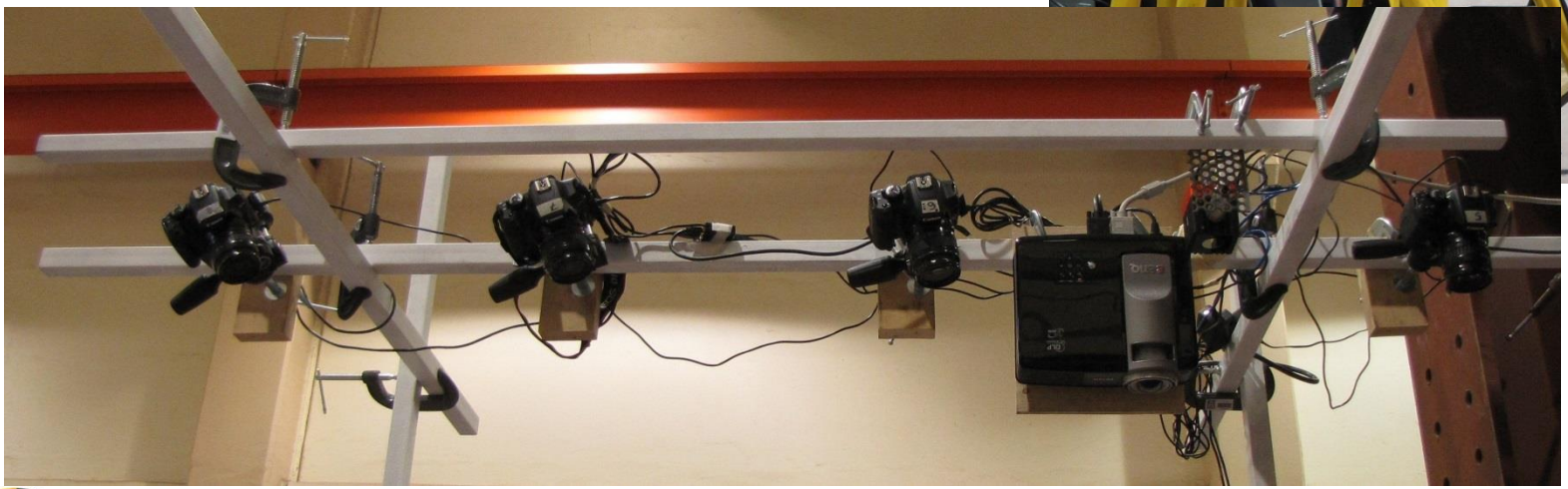
Fine-scale level:

- Measurement of deflections and cracks in structural components
- Provision of feedback for structural design improvements



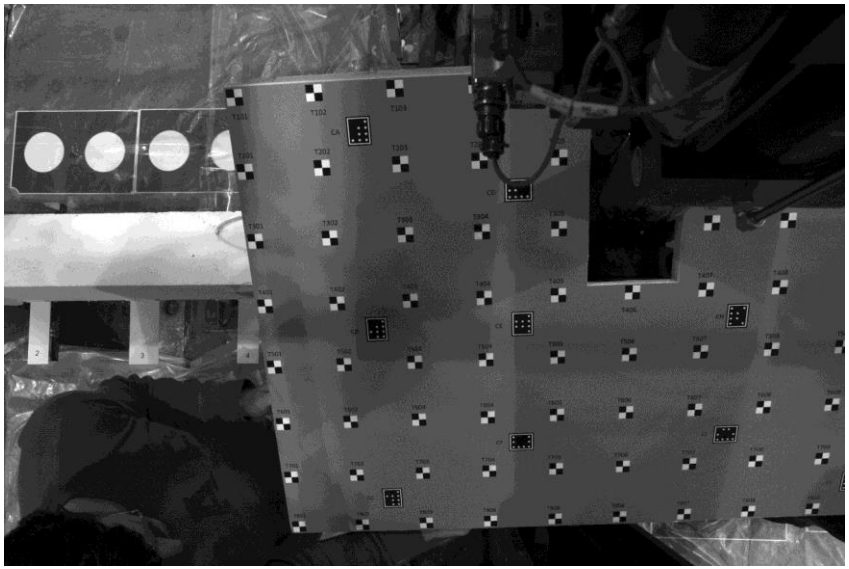
Proposed photogrammetric systems

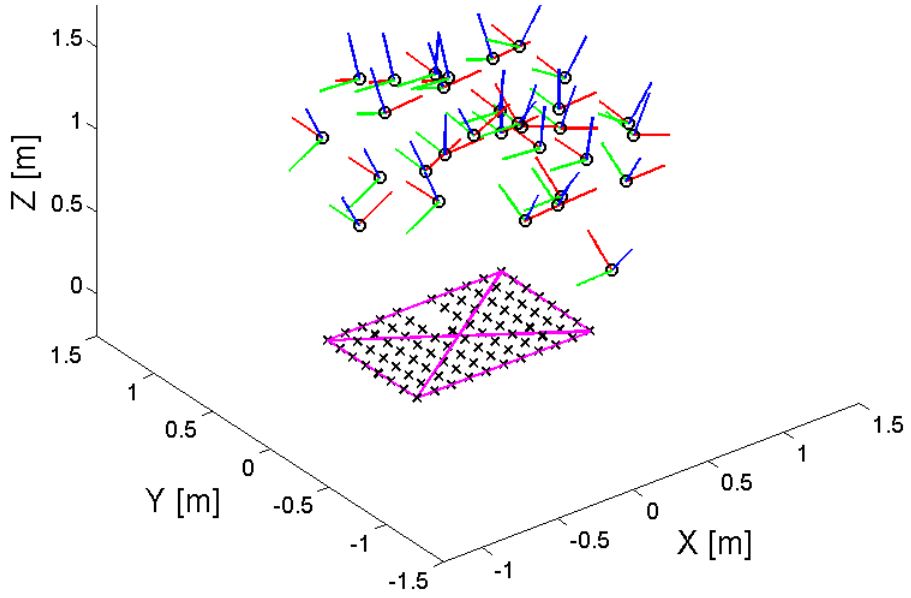
- Standing/upright system for crack observations
- Suspended/overhanging system for deflection measurements



In-situ multi-system calibration

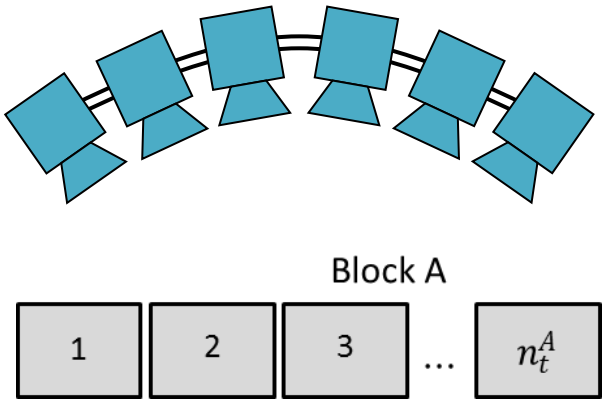
- Series of rotations and translations of a portable 2D test field
- Simultaneous estimation of interior orientation (IOPs) and camera mounting (CMPs) parameters



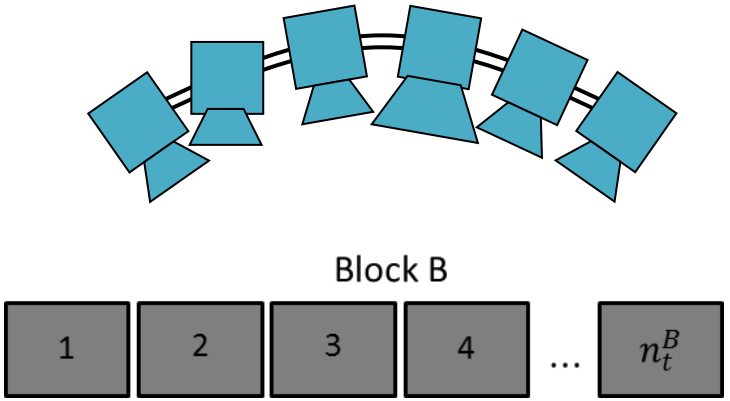


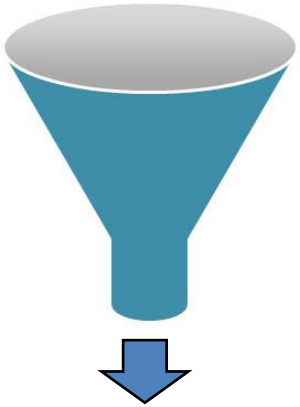
System stability analysis

IOPs and CMPs at t_1



IOPs and CMPs at t_2





XYZ

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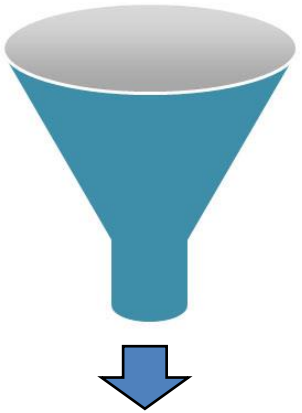


XYZ

System stability methodologies

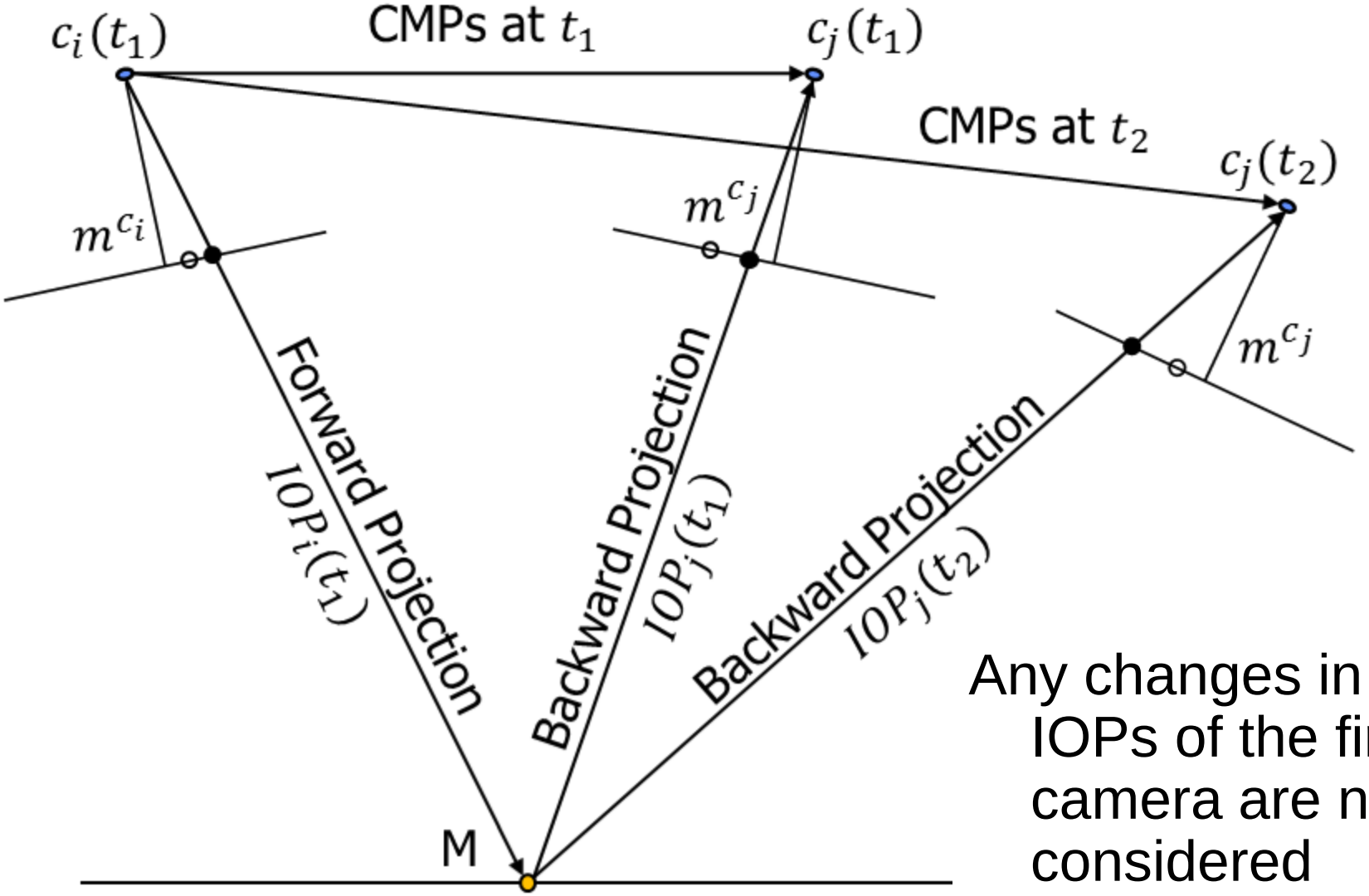
Concept:

- Numerical tool for checking the impact of different sets of calibration parameters

Methods:

- Method 1: combination of forward and backward projections
- Method 2: object space parallax in image space units
- Method 3: variation in normalized image coordinates

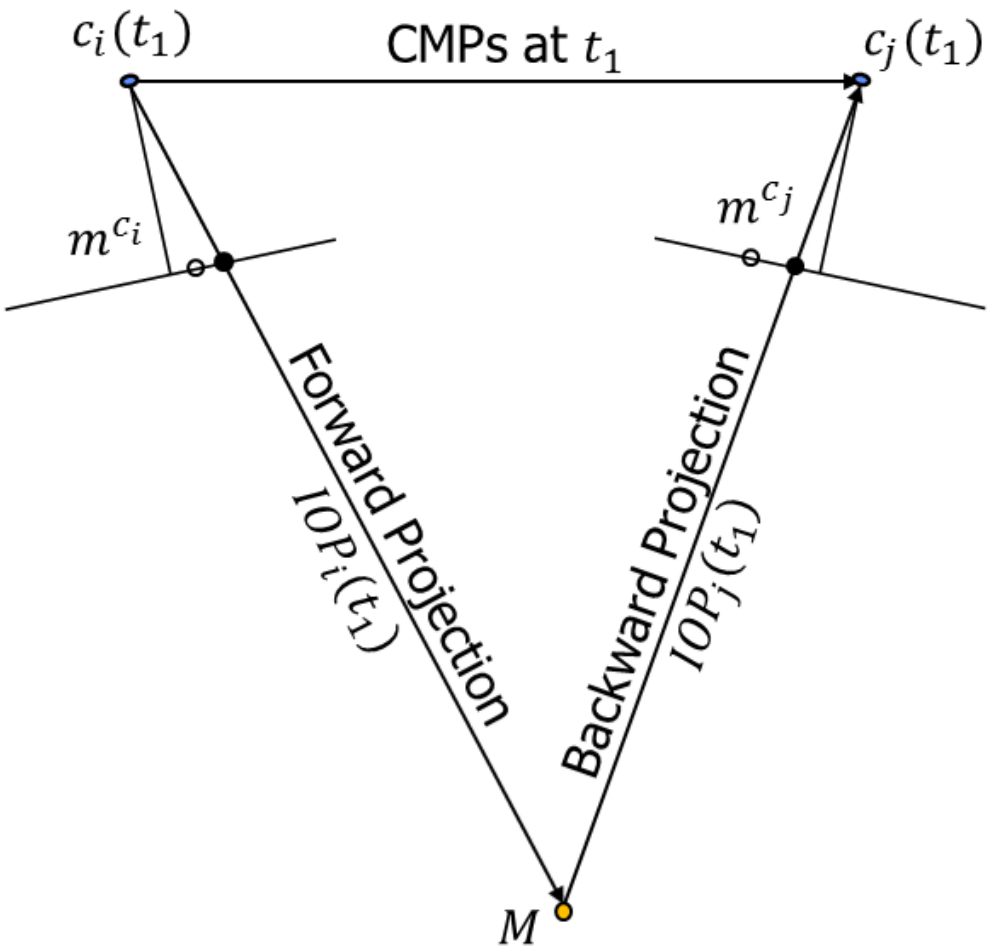
Method 1



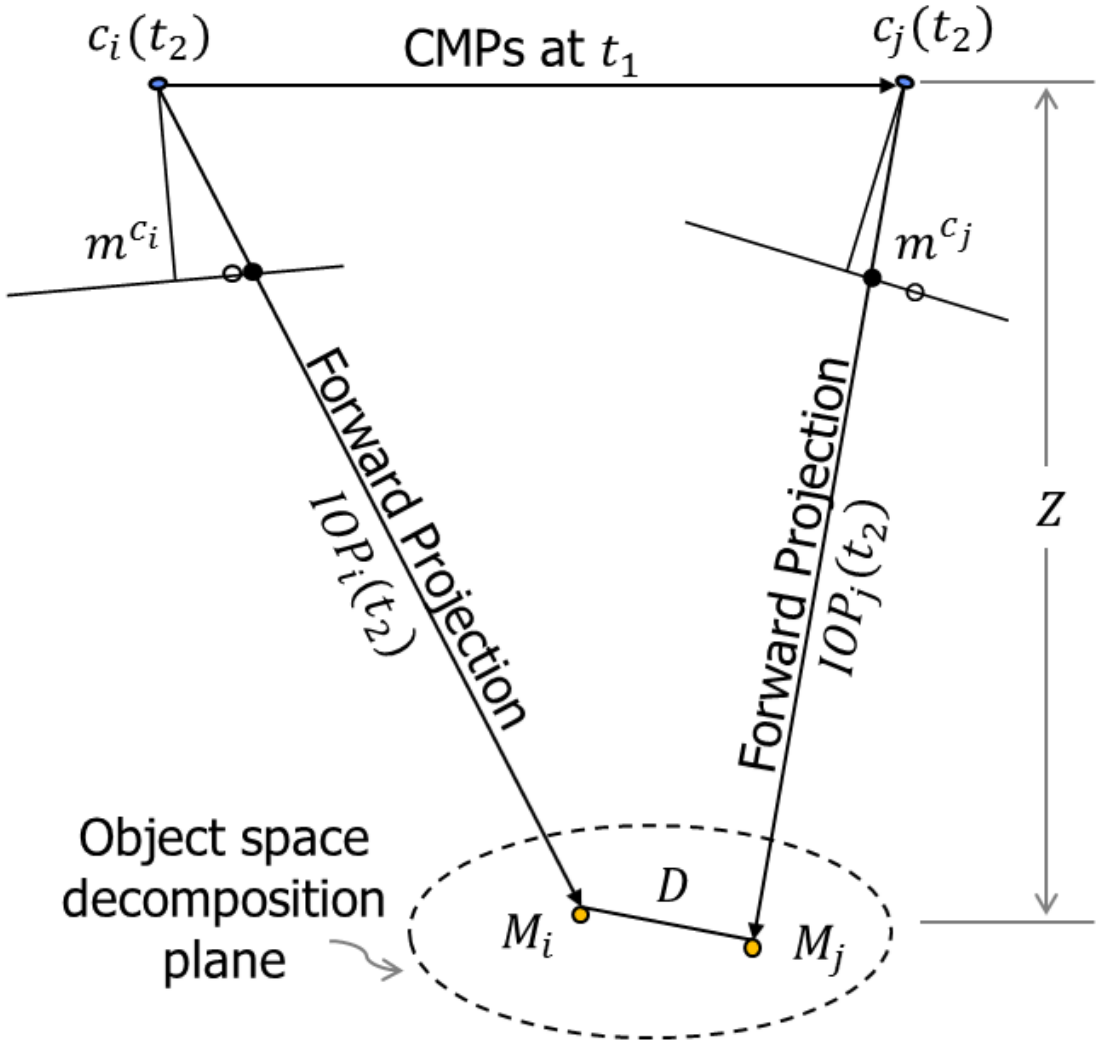
Any changes in the IOPs of the first camera are not considered

Method 2 (1/2)

Obje ts

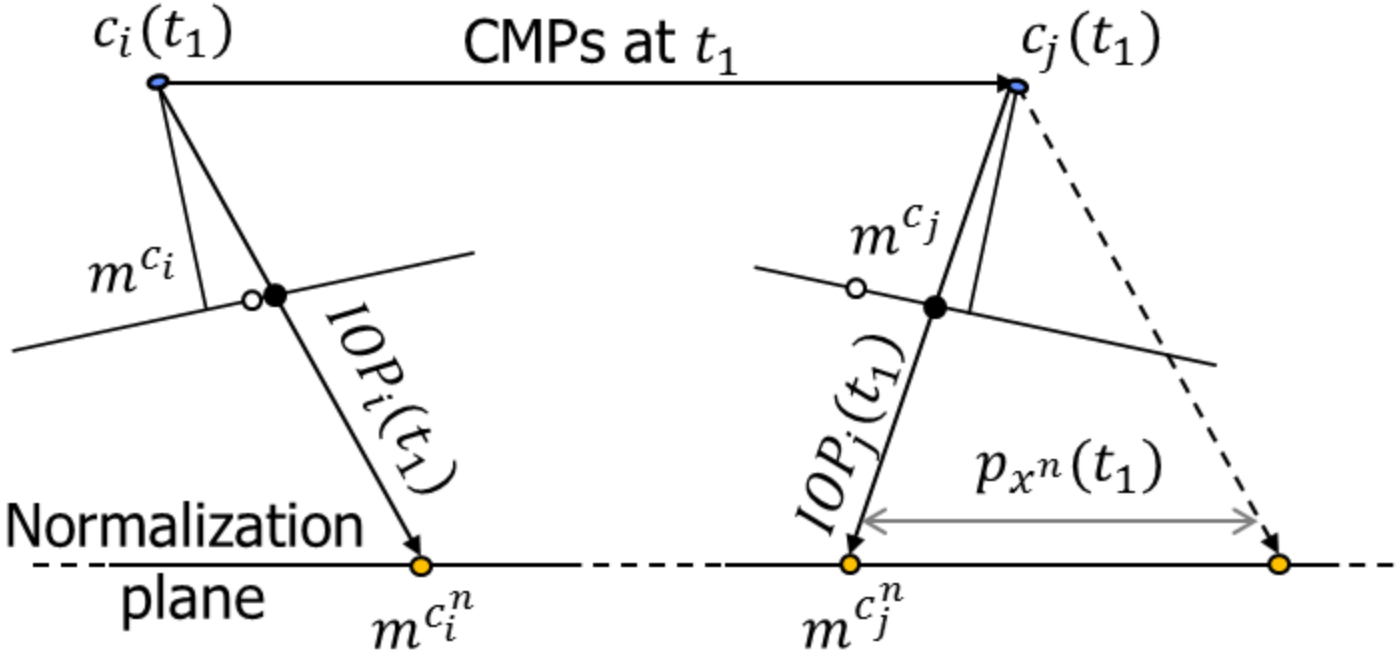


Method 2 (2/2)


$c_i(t_2)$
CMPs at t_1
$c_j(t_2)$
m^{c_i}
m^{c_j}
Forward Projection
$IOP_i(t_2)$
Forward Projection
$IOP_j(t_2)$
Z
Object space
decomposition
plane
D
M_i
M_j

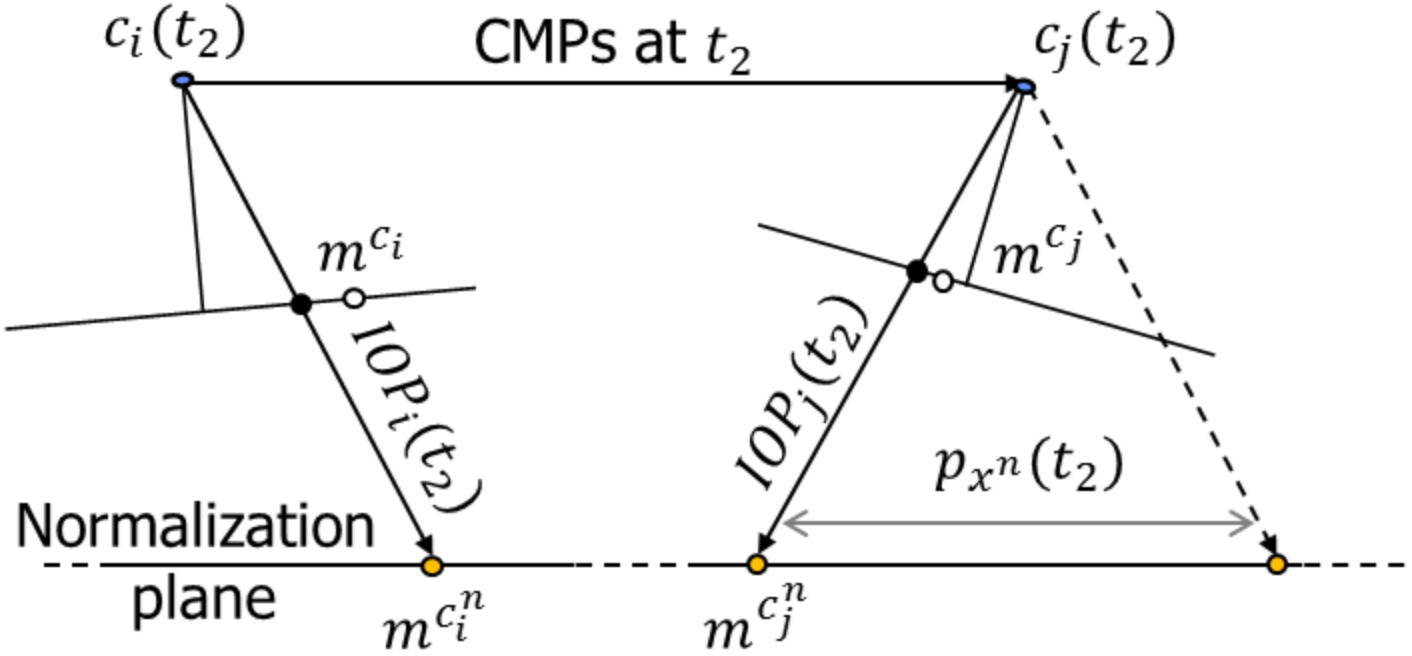
Method 3 (1/2)

Variation in the normalized image coordinates



Method 3 (2/2)

Variation in the normalized image coordinates



Any changes in the magnitude/extent of the baseline would not be picked up

Conducted tests

Simulation of changes in the IOPs and CMPs

- Method 1 vs. Method 2 comparison
- Method 3 vs. Method 2 comparison
- Decide which method works best in the most general case

Real world tests

- System stability analysis for a multi-day experiment
- Same-day system stability analysis
- Come up with recommendations on the frequency of calibration and/or locating any (source of) instability

Simulation of changes in IOPs & CMPs

- Biases applied one by one to each odd-numbered camera in a system
- Magnitude of biases chosen to cause noticeable instability

Parameters	Biases	Units
x_p, y_p, c	+50 or +100	[µm]
k_1, k_2	$+5\text{x}10^{-5}$ or $+5\text{x}10^{-7}$	[mm^{-2}] or [mm^{-4}]
p_1, p_2	$+1\text{x}10^{-5}$	[mm^{-1}]
b_X, b_Y, b_Z	+5	[mm]
$b_\omega, b_\varphi, b_\kappa$	+0.1	[°]

Changes in the IOPs (1/2)

Parameters / cam pairs	Method 1	Method 2	Method 3
	Total RMSE [px] for Cams 4 & 5		
None	0.00	0.00	0.00
Δx_p	8.76	8.96	8.98
Δy_p	8.76	8.95	8.91
Δc	5.25	5.43	5.47
Δk_1	4.85	4.95	5.03
Δk_2	5.15	5.17	5.26
Δp_1	0.27	0.28	0.29
Δp_2	0.16	0.17	0.17

Changes in the IOPs (2/2)

Parameters / cam pairs	Method 1	Method 2	Method 3
	Total RMSE [px] for Cams 3 & 4		
None	0.00	0.00	0.00
Δx_p	0.00	8.83	8.90
Δy_p	0.00	8.82	8.84
Δc	0.00	6.18	4.46
Δk_1	0.00	2.84	2.91
Δk_2	0.00	2.17	2.23
Δp_1	0.00	0.18	0.19
Δp_2	0.00	0.13	0.13

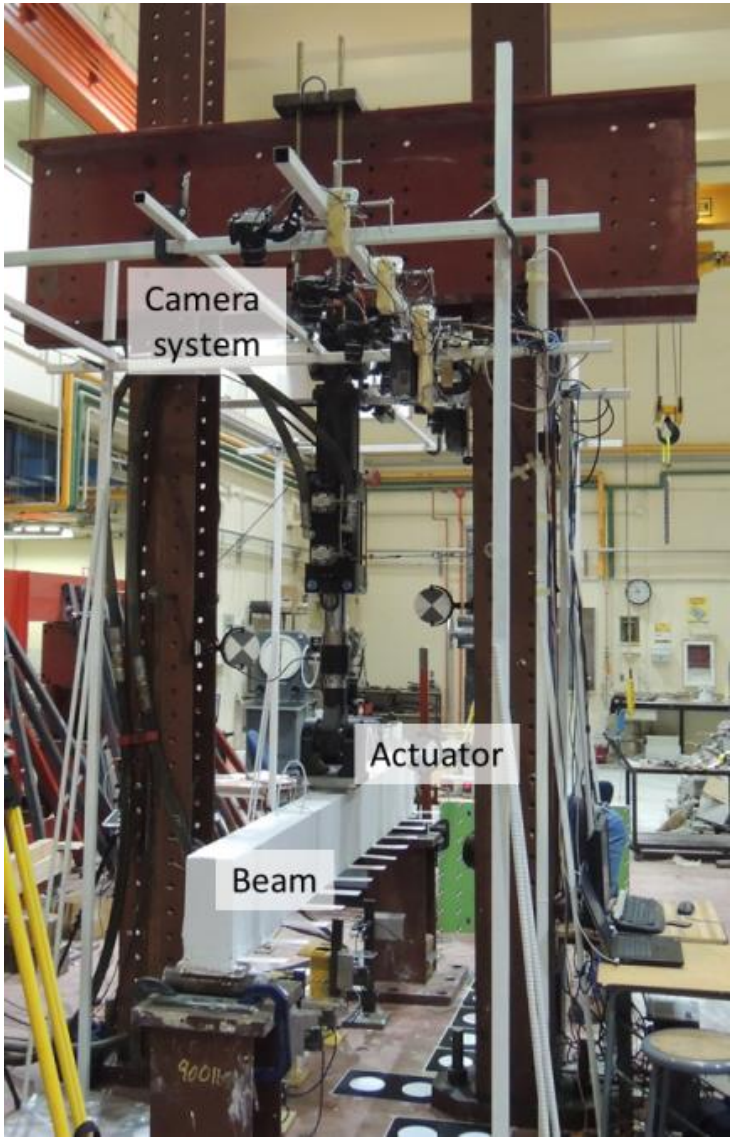
Method 1 does not perform adequately in the scenario when the IOPs of the first camera are changed

Changes in the CMPs

Parameters / cam pairs	Method 1	Method 2	Method 3
	Total RMSE [px] for Cams 3 & 4		
None	0.00	0.00	0.00
Δb_X	10.57	11.05	0.15
Δb_Y	10.62	10.89	10.91
Δb_Z	3.15	3.40	4.48
Δb_ω	6.86	7.04	7.05
Δb_φ	6.70	7.01	7.27
Δb_κ	1.72	1.76	1.77

Method 3 does not perform adequately in the scenario when there are changes in the extent of the baseline

Example photogrammetric system (1/2)



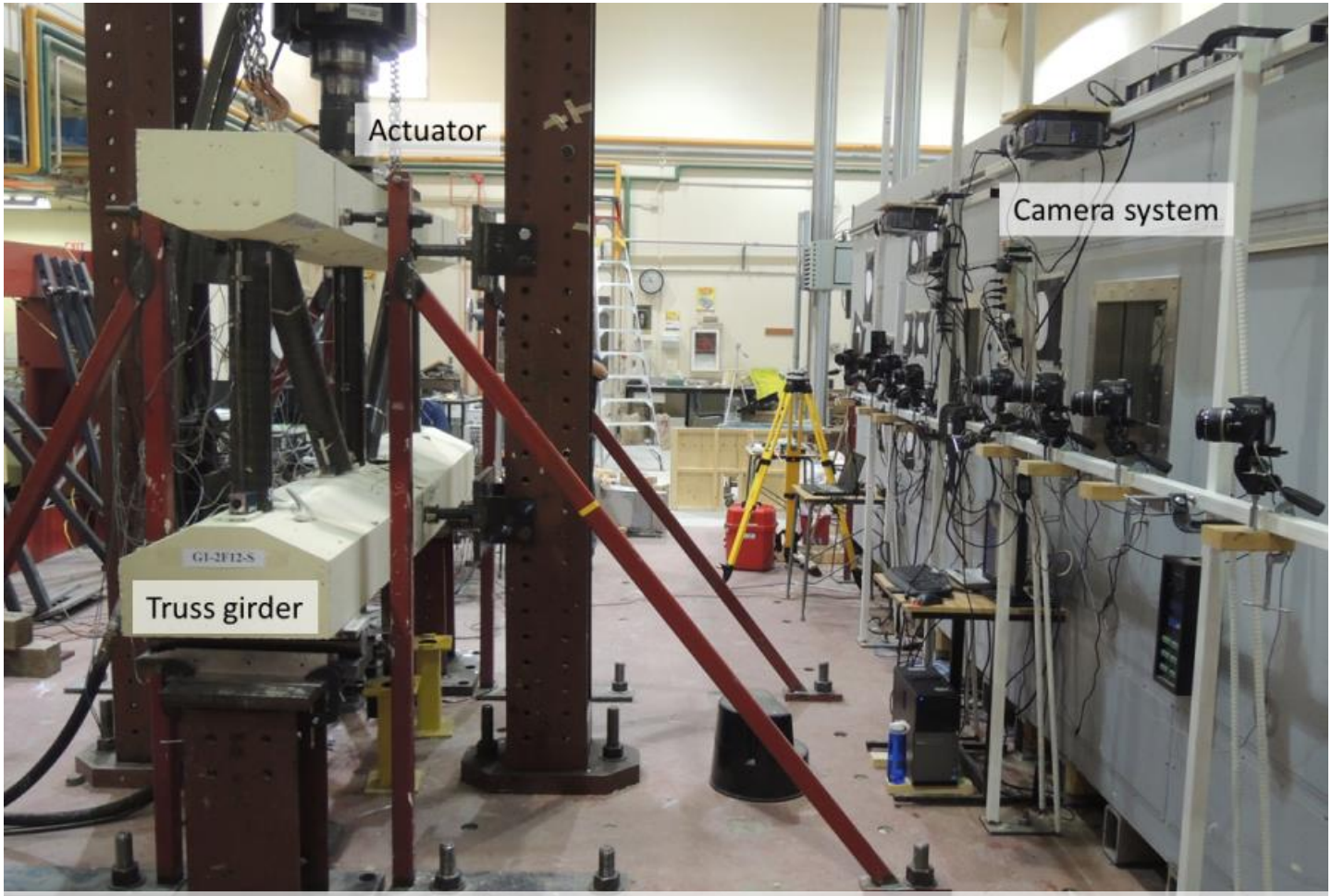
Suspended / overhanging system for deflection measurements

Multi-day system stability test

Cam pairs / RMSEs	Total RMSE [px]	
	Day 1 vs. Day 2	Day 2 vs. Day 3
Cams 1 & 2	0.64	0.92
Cams 2 & 3	1.02	1.02
Cams 3 & 4	0.44	0.56
Cams 4 & 5	1.05	0.48
Cams 5 & 6	1.75	0.60
Cams 6 & 7	1.09	0.71
Cams 7 & 8	1.10	2.41

Increase the calibration frequency from once to twice daily
(i.e., before start and after end of each daily experiment)

Example photogrammetric system (2/2)



Standing/upright system for crack observations

Same day system stability test

Cam pairs / RMSEs	Total RMSE [px]	
	Pre vs. Mid	Mid vs. Post
Cams 1 & 2	0.96	0.28
Cams 2 & 3	0.39	0.66
Cams 3 & 4	0.21	0.41
Cams 4 & 5	0.79	0.33
Cams 5 & 6	0.53	0.24
Cams 6 & 7	0.72	0.68
Cams 7 & 8	1.55	1.02

Potential source of instability in the vicinity of Cam 8

Conclusions

Three methods for performing system stability analysis were presented:

- All based on synthetic grids in image space, and pairwise relationship between neighbouring cameras
- Method 2 yields the best measure of (in)stability in the most general case
- Results help with deciding on the required frequency of calibration
- Any system instability can be pin-pointed, and potentially mitigated

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Traditional instrumentation

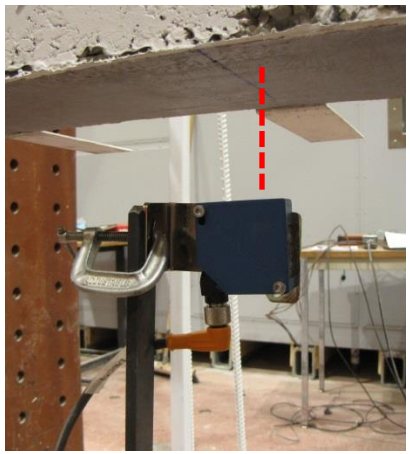
Deflection measurements

- Laser transducers, fibre optic sensors, wire strain gauges

http://www.instron.com/fileuniverse/live/images/Accessories/2601-093_P.jpg

Crack observations

- Strain gauges, crack oculars, crack width templates



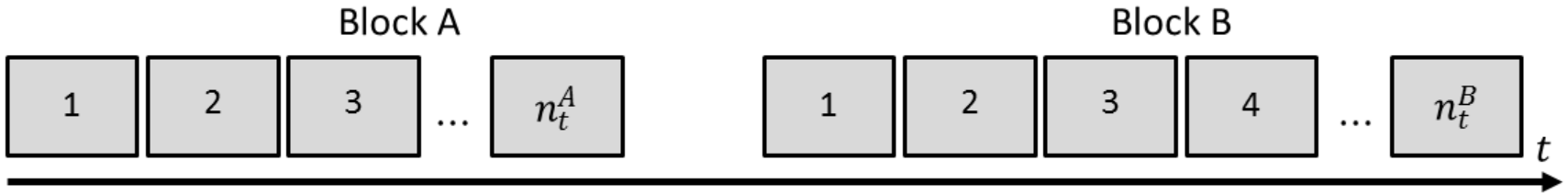
http://upload.wikimedia.org/wikipedia/commons/b/b1/Hudson-Athens_Strain_Gauge.jpg

http://www.peplertech.co.uk/wp-content/uploads/wpsc/product_images/RL-6-2.jpg

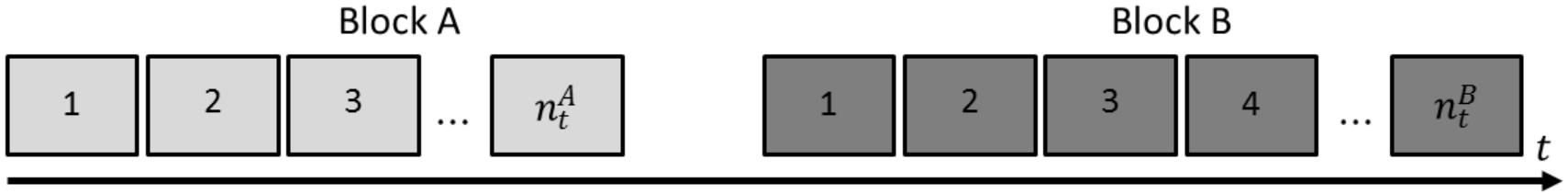
http://www.emeraldinsight.com/content_images/fig/

Camera (in)stability scenarios

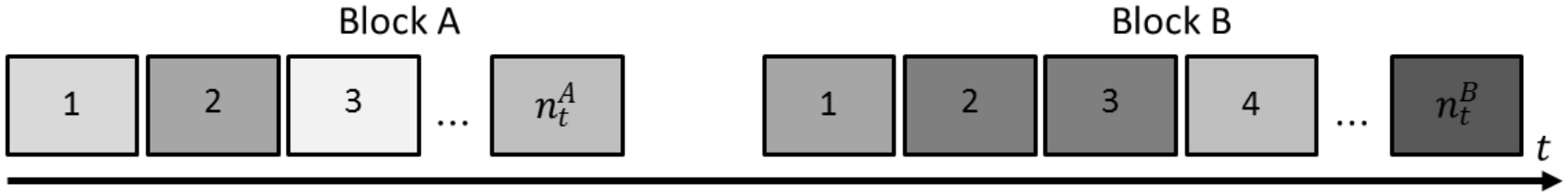
a) No instability



b) Instability between different blocks



c) Instability within a block



System stability analysis

Do the 3D reconstruction results differ depending on the set of system calibration parameters used?