LISBOA 2010
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A Non-Contact Measurement System for Monitoring the Displacements of Long Deck Suspension Bridges

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INTRODUCTION

- Structural Health Monitoring of long deck suspension bridges.

⇒ Measurement of the vertical and transversal displacements.

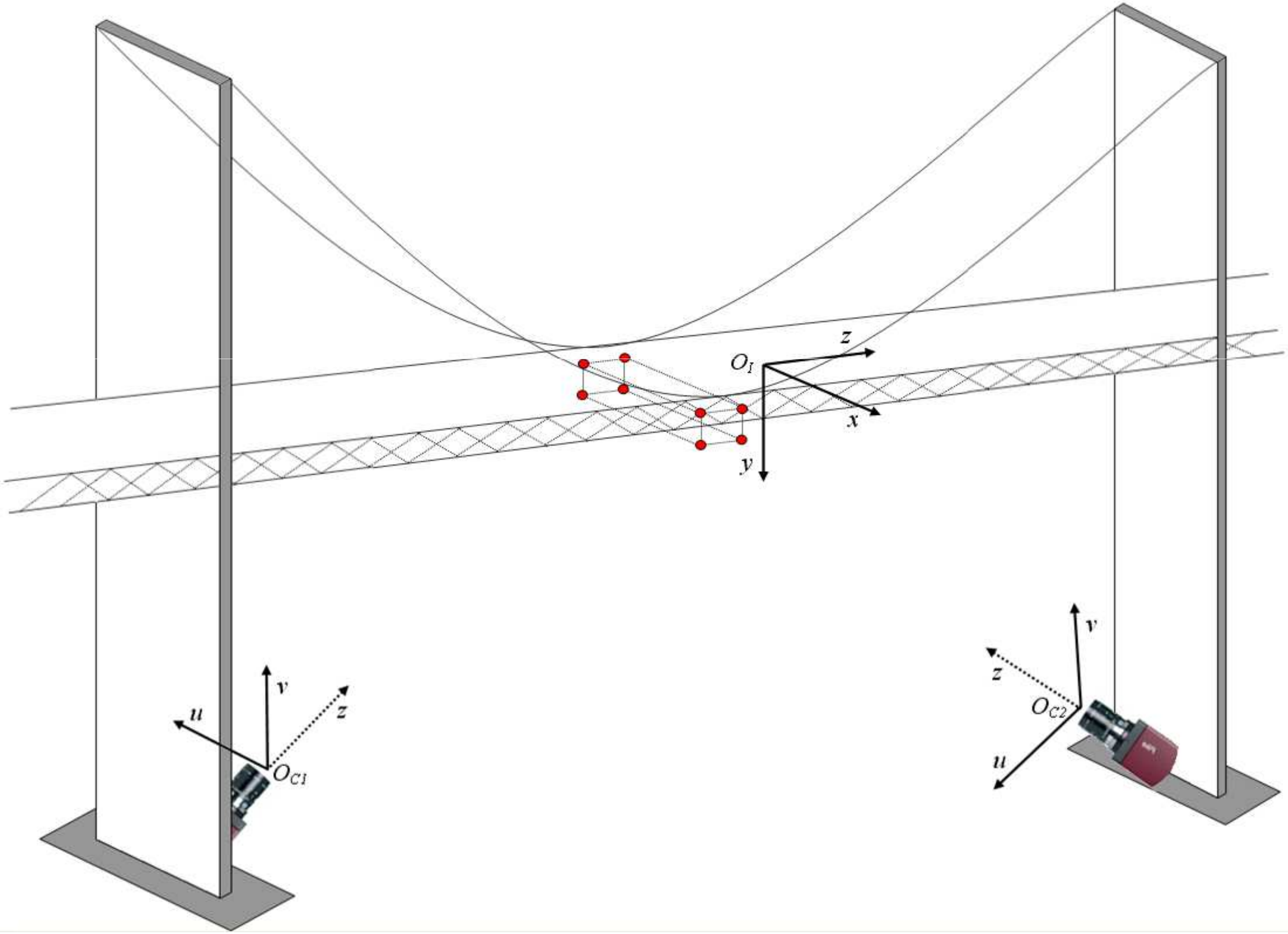
- There is no fixed point in the vicinity of the zone to monitor;
- Displacements with high amplitude (> 1 m).

⇒ Non-contact measurement system, using optical devices and image processing techniques.

INTRODUCTION

- Measurement of the vertical and transversal displacements of the deck bridge satisfying the specifications:
  - Range amplitude ≥ 2 m;
  - Accuracy (vertical/transversal) better than ± 10 mm;

WORKING PRINCIPLE

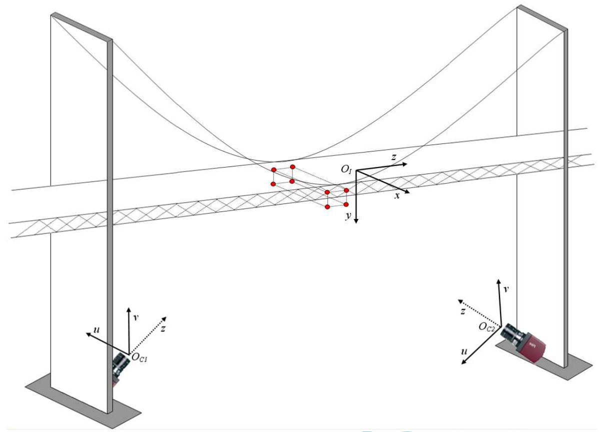


WORKING PRINCIPLE

- The high resolution digital cameras, coupled to long focal length lenses, are fixed in the pier's base (reference points) – minimum of 2;
- A set of active targets are fixed in the deck bridge (monitoring points);
- The position of the targets is captured by the cameras;
- Determination of the position of the targets by triangulation.

⇓

Calibration of the Vision System



AFFINE CAMERA MODEL

- The target $P = [X, Y, Z]^T$ in the deck is projected in the image at the coordinates $c = [u, v]^T$, according to:

$$\begin{bmatrix} u - u_0 \\ v - v_0 \end{bmatrix} = \underbrace{\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \end{bmatrix}}_{M} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

- *M* – camera projection matrix;

- The point $c_0 = [u_0,\ v_0]^T$ represents the image of the origin of the coordinate system settled in the deck bridge.

CALIBRATION PROBLEM

- If the 3D coordinates of a set of targets are known, as well as their projection in the image, then the matrix *M* may be easily determined.

$$\begin{bmatrix} u - u_0 \\ v - v_0 \end{bmatrix} = \underbrace{\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \end{bmatrix}}_{M} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

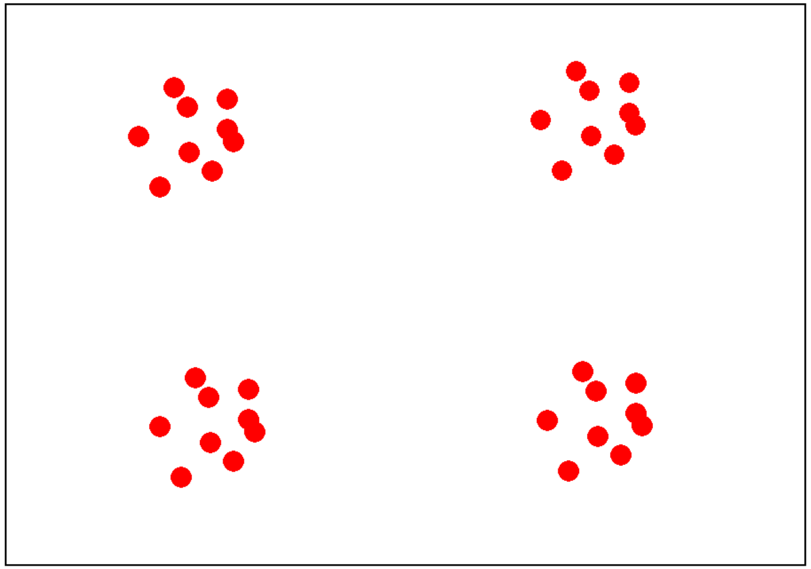
- PROBLEM: It is not possible to know the coordinates of the targets, since the deck bridge is moving.

CALIBRATION METHODOLOGY: REQUIREMENTS

- A minimum of two cameras (digital camera + lens);
- A set of active targets fixed in the deck bridge such as all are viewed by all cameras;
- The deck zone where the targets are fixed behaves like a rigid body;
- The knowledge of the distance between the targets.

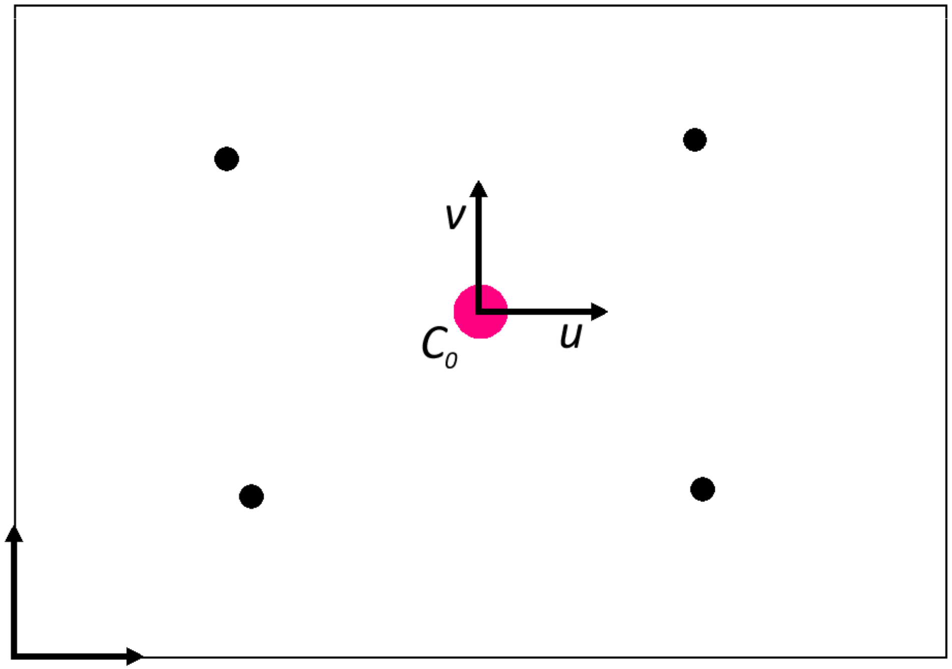
CALIBRATION METHODOLOGY

- A set of images is captured, while the deck bridge (targets) is in motion.
- For each camera, we determine the coordinates of the centroid of the points of each cloud – *average frame*.



CALIBRATION METHODOLOGY

- The coordinate system of each camera is settled at the centroid of this new data set, defined as $c_0 = [u_0, v_0]^T$.



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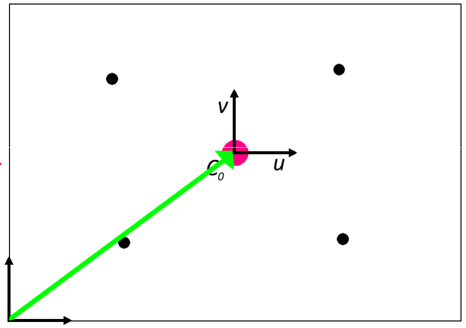
CALIBRATION METHODOLOGY

- Considering *n* cameras and *m* targets, we have a set of observations, defined by the matrix *W*.

$$\begin{bmatrix} u_i - u_0 \\ v_i - v_0 \end{bmatrix} = \underbrace{\begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \end{bmatrix}}_{M} \cdot \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix}$$



$$\underbrace{\begin{bmatrix} (u_1^1 - u_0^1) & \cdots & (u_m^1 - u_0^1) \\ (v_1^1 - v_0^1) & \cdots & (v_m^1 - v_0^1) \\ \vdots & \ddots & \vdots \\ (u_1^n - u_0^n) & \cdots & (u_m^n - u_0^n) \\ (v_1^n - v_0^n) & \cdots & (v_m^n - v_0^n) \end{bmatrix}}_{W} = \underbrace{\begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix}}_{M} \cdot \underbrace{\begin{bmatrix} P_1 & \cdots & P_m \end{bmatrix}}_{P}$$

2n x 3

3 x m

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CALIBRATION METHODOLOGY

- Since the rank of $W \leq 3$, applying a single value decom-position to W, we obtain an estimative for M and P.

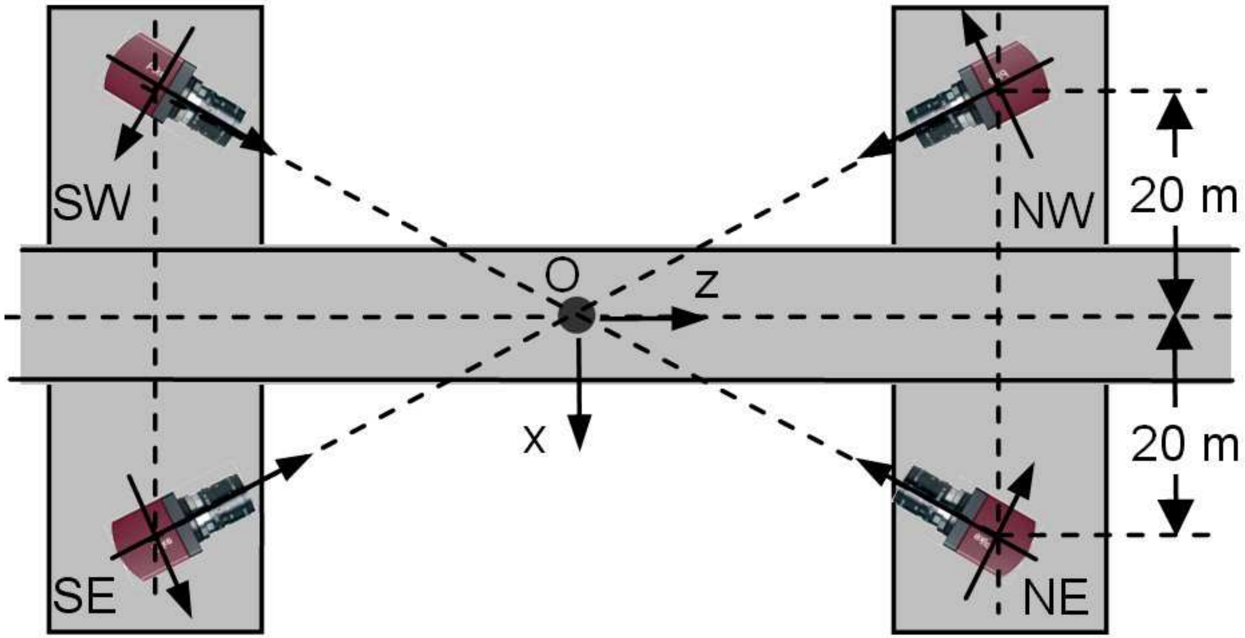
$$\underbrace{\begin{bmatrix} (u_1^1 - u_0^1) & \cdots & (u_m^1 - u_0^1) \\ (v_1^1 - v_0^1) & \cdots & (v_m^1 - v_0^1) \\ \vdots & \ddots & \vdots \\ (u_1^n - u_0^n) & \cdots & (u_m^n - u_0^n) \\ (v_1^n - v_0^n) & \cdots & (v_m^n - v_0^n) \end{bmatrix}}_{W} = \underbrace{\begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix}}_{M} \cdot \underbrace{\begin{bmatrix} P_1 & \cdots & P_m \end{bmatrix}}_{P}$$

$$\boxed{W = U \cdot D \cdot V^T}$$

$$\underbrace{\begin{bmatrix} M_1 \\ \vdots \\ M_n \end{bmatrix}}_{M} = U_{2nx3} \cdot \sqrt{D_{3x3}} \qquad \underbrace{\begin{bmatrix} P_1 \\ \vdots \\ P_m \end{bmatrix}}_{P}^{T} = \sqrt{D_{3x3}} \cdot V_{mx3}^T$$

NUMERICAL SIMULATION TESTS

- Results for 2 cameras layouts:
  - 2 Cameras -> S – N;
  - 4 Cameras -> SE – SW – NE – NW.



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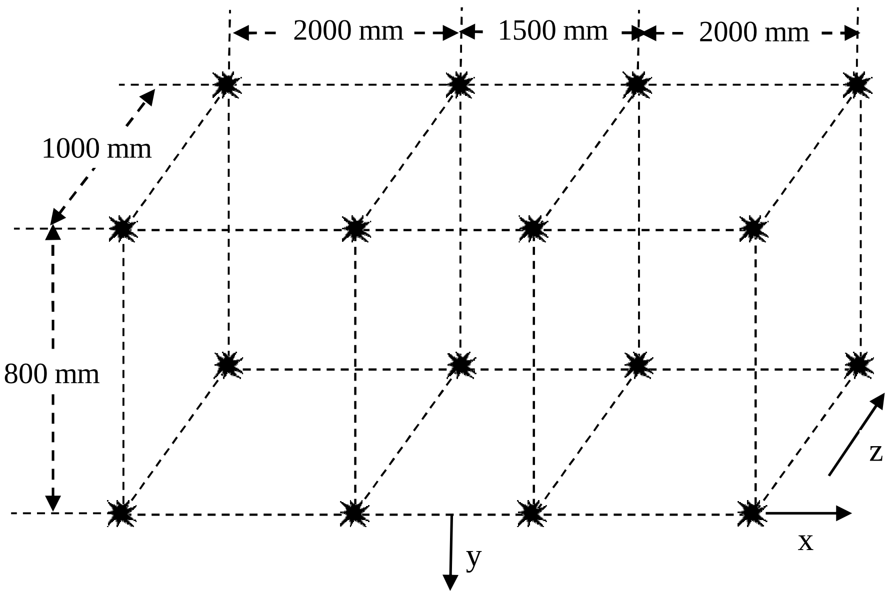
ASSUMPTIONS (CALIBRATION)

- Optical system specifications:
  - Resolution = 1920 x 1080 pixel
  - Focal length = 600 mm;
- 16 targets. The distance between the targets is known.



ASSUMPTIONS (CALIBRATION)

- 1000 images were captured by each camera, synchronously;

- Since the true coordinates are known (created by numerical simulation), a random disturbance (noise) was added to the coordinates in the images to simulate the several sources of error (e.g. image processing, sensor's camera noise).

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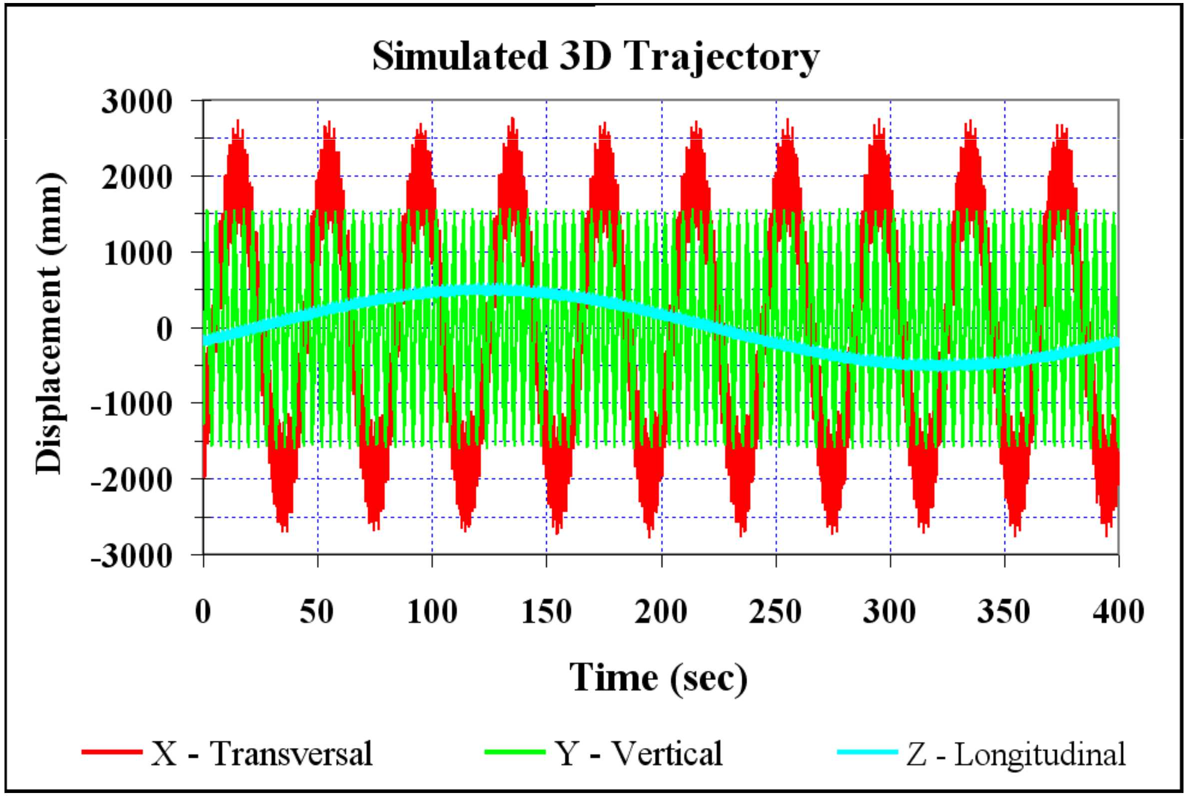
TEST 1 (MONITORING)

- Simulated 3D deck bridge trajectory used in the monitoring stage, with 10,000 positions.

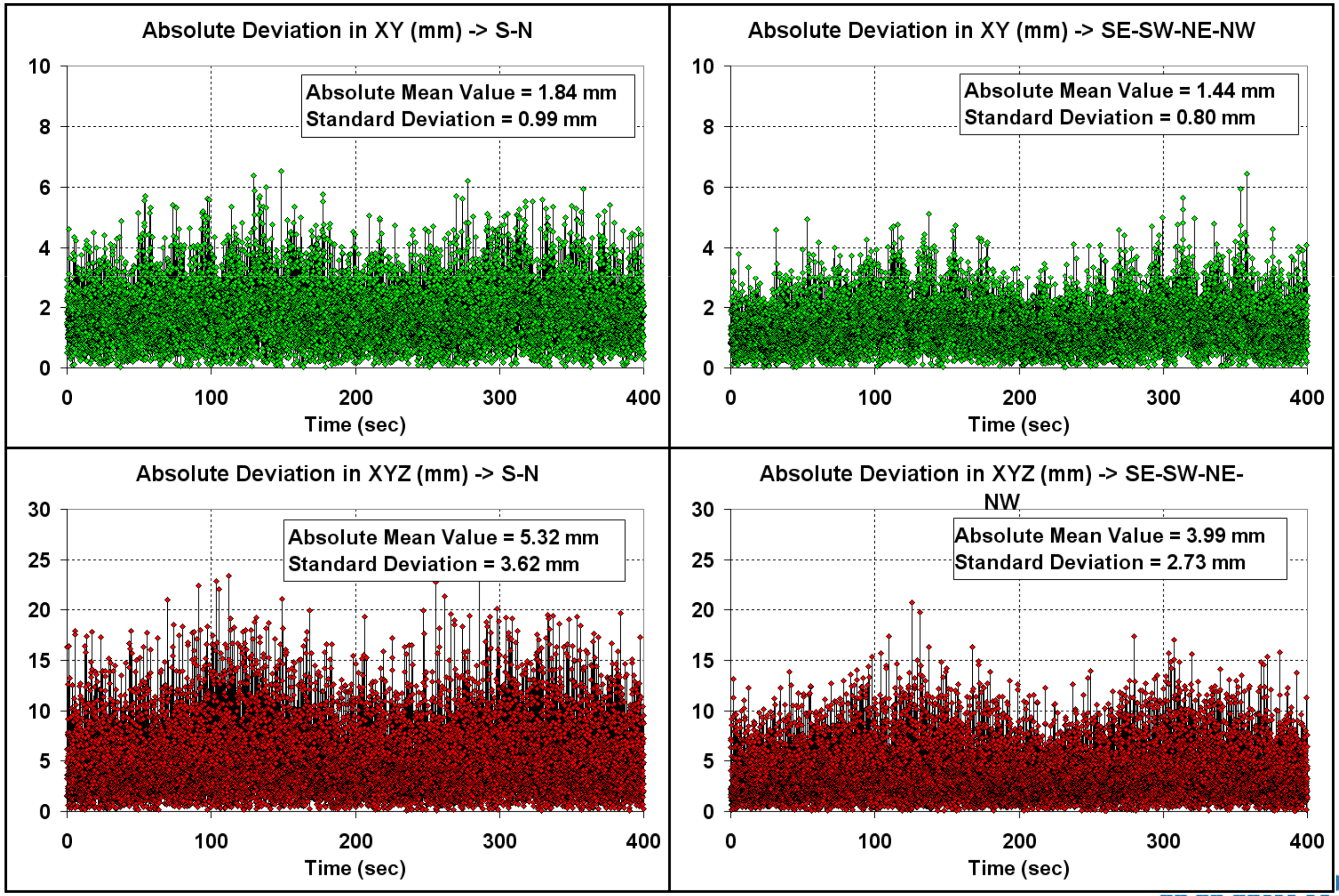


RESULTS (OBTAINED BY NUMERICAL SIMULATION)

- Absolute position deviation (disturbance = 1 pixel).

Plan

Global



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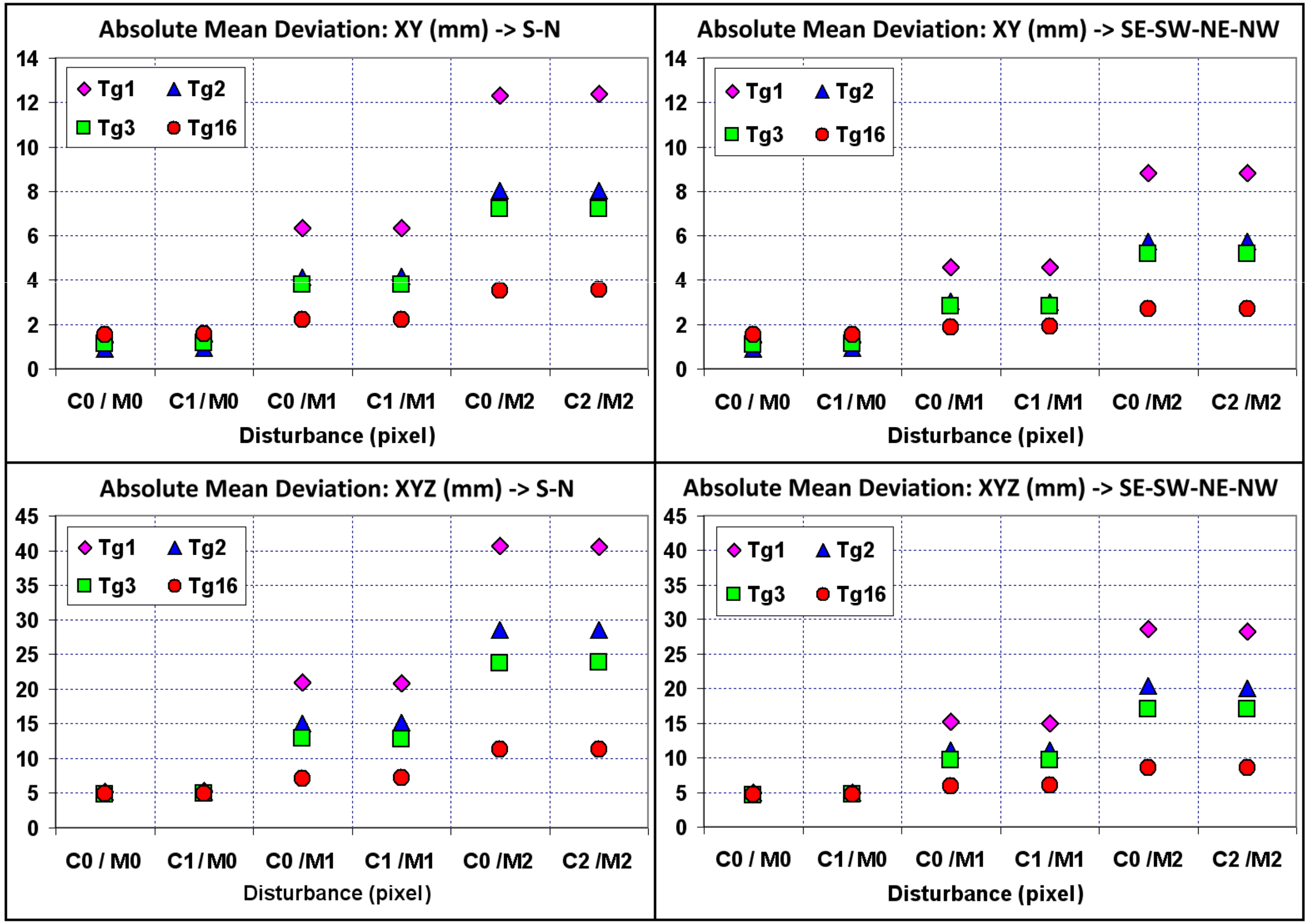
RESULTS (OBTAINED BY NUMERICAL SIMULATION)

- Absolute mean deviation (position).



- *TgN* – *N* targets used in the moni-toring stage;
- *Cm/Mn* – *m* pixel of disturbance in the cali-bration and *n* pixel in the monitoring stages.

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CONCLUSIONS

- The vision system calibration can be carried out in-situ and only requires a minimum of two cameras, a set of targets fixed in the deck and the knowlegde of the distance between them;
- The results obtained by numerical simulation confirm the good feasibility and robustness of the calibration methodology to disturbance, even under severe conditions;
- The required accuracy ($\pm$ 10 mm) in the vertical/transversal directions, even considering high severe conditions of disturbance level (2 pixel), may be fulfilled with 2 cameras and 2 targets or 4 cameras and 1 target.

Thank you