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.

- There is no fixed point in the vicinity of the zone to monitor;

- Displacements with high amplitude (> 1 m).

Measurement of the vertical and transversal displacements.

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:

$$
\begin{bmatrix}
u - u_0 \\
v - v_0
\end{bmatrix} = M \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}
$$

- $M$ – 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.

- **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*. 

![Diagram showing points of each cloud]
The coordinate system of each camera is settled at the centroid of this new data set, defined as $c_0 = [u_0, v_0]^T$. 
CALIBRATION METHODOLOGY

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

\[
\begin{bmatrix}
u_i - u_0 \\ v_i - v_0 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \end{bmatrix} \begin{bmatrix} X_i \\ Y_i \\ Z_i \end{bmatrix}
\]

\[
\begin{bmatrix}
(u_1^1 - u_0^1) \\
(v_1^1 - v_0^1) \\
\vdots \\
(u_n^1 - u_0^1) \\
(v_1^n - v_0^n) \\
\vdots \\
(u_m^1 - u_0^1) \\
(v_m^n - v_0^n)
\end{bmatrix} = \begin{bmatrix}
M_1 \\
\vdots \\
M_n
\end{bmatrix} \cdot \begin{bmatrix}
P_1 \\
\vdots \\
P_m
\end{bmatrix}
\]

\(2n \times 3\)

\(3 \times m\)

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

\[
\begin{bmatrix}
(u_1^1 - u_0^1) & \cdots & (u_m^1 - u_0^1) \\
(v_1^1 - v_0^1) & \cdots & (v_m^1 - v_0^1) \\
\vdots & \ddots & \vdots \\
(u_1^n - u_0^n) & \cdots & (u_m^n - u_0^n) \\
(v_1^n - v_0^n) & \cdots & (v_m^n - v_0^n)
\end{bmatrix}
= \begin{bmatrix}
M_1 \\
\vdots \\
M_n
\end{bmatrix}
\begin{bmatrix}
P_1 \\
\vdots \\
P_m
\end{bmatrix}
\]

$W = U \cdot D \cdot V^T$

\[
\begin{bmatrix}
M_1 \\
\vdots \\
M_n
\end{bmatrix}
= U_{2nx3} \cdot \sqrt{D_{3x3}}
\]

\[
\begin{bmatrix}
P_1 \\
\vdots \\
P_m
\end{bmatrix}^T
= \sqrt{D_{3x3}} \cdot V_{mx3}^T
\]
NUMERICAL SIMULATION TESTS

- Results for 2 cameras layouts:
  - 2 Cameras -> S – N;
  - 4 Cameras -> SE – SW – NE – NW.
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).
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
RESULTS (OBTAINED BY NUMERICAL SIMULATION)

- Absolute mean deviation (position).

- $TgN$ – $N$ targets used in the monitoring stage;

- $Cm/Mn$ – $m$ pixel of disturbance in the calibration and $n$ pixel in the monitoring stages.
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 knowledge 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 (± 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