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SELECTION OF PARAMETERS IN SPR CAMERA SYSTEM FOR STRUCTURAL HEALTH MONITORING OF UAV MAIN WING

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Abstract

Structural deformation monitoring of main wing of high speed aircraft is important issue in that it undergoes higher level of deformation because of the airflow condition it goes through. Stereo Pattern Recognition (SPR), the vision-based deformation measurement method using stereo camera set and reflective markers, is considered to be a suitable method for in-flight structure deformation measurement since it shows reasonable accuracy with simpler system configuration. Even if the hardware set-up is simple, there are many parameters affect the measurement performance of SPR camera system. In this paper, parameters of SPR camera system for specific wing vibration conditions are determined according to defined error criteria, using developed simulation software for effective and quantitative job.

1 Introduction

Traditionally, accelerometer, strain gauge or FBG sensor has been utilized to deformation measurement of structure. [1-3] However, in recent days, application of the vision-based deformation measurement techniques is made on various researches to overcome the limits and disadvantages in traditional methods. The Stereo Pattern Recognition (SPR) method, which utilizes image data obtained from multiple cameras to measure deformation, is widely used for this purpose. [4-6] Generally a number of markers are attached on the structure surface to give structure deformation data. It's a preferable technique since it's not only non-intrusive but a full-field shape measurement method with sufficient accuracy. [7] This full-field measurement technique is applicable in aeroelastic flutter test, because it directly gives deformation of the whole structure and also it does not affect the structure characteristics.

Even though configuration of SPR measurement system is clear and simple, its measuring performance is dependent on many system parameters such as camera intrinsic and extrinsic parameters, marker distribution and size. These system parameters should be determined considering the motion and dimension of the target structure. For these reasons mentioned, it is preferable to design the SPR measurement through the simulation rather than the experiment. For this purpose, the simulation framework named 'SPR Interactive Modeling and Simulation (SIMS)' has been developed and introduced in previous work. [6] In it, the formulation and working process of SIMS is described. In addition, the validity of using the framework to improve the performance of SPR system was shown via comparison between the simulation and experiment result using thin acrylic plate as a target structure.

In this paper, the sensitivity analysis of camera intrinsic parameter has been done as a further study of previous work. Using thin wing-shaped plate as a target structure, measurement performance of SPR system is evaluated based on decided error criteria. Three camera intrinsic parameters, camera shutter speed, sensor resolution and frame rate are chosen as parameter of interest. The measurement performance sensitivity with respect to these parameters is evaluated. This sensitivity result would be useful in deciding camera specifications, and further the SPR system set-up.

2 Background

2.1 SPR Method

SPR method is a vision-based displacement measure technique, which utilizes the position of a 'keypoint' on the structure surface as a displacement data of attached structure point. The image of keypoins, usually a reflective markers, are taken by stereo camera set. The conceptual diagram of SPR system is as shown in Fig. 1.

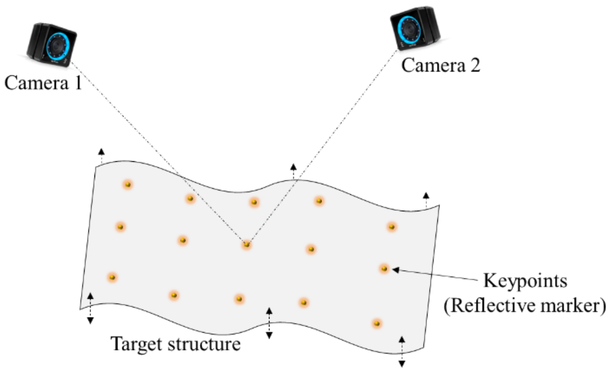

Figure 1. General configuration of SPR system

The image obtained are processed to get 3D position data of keypoints. To ease the image processing, IR reflective markers are used as keypoins, and each camera has IR band pass filter in front of the sensor.

2.2 Estimate 3D Position Using Stereo Image

When the target image is taken by a camera, it projects to camera image plane. (Fig. 2) Relationship between the camera image plane coordinate and camera 3D coordinate is given as equation (1).

$$\lambda \begin{Bmatrix} x^{c,i} \\ y^{c,i} \\ 1 \end{Bmatrix} = \begin{bmatrix} \gamma f & sf & x_0 \\ 0 & f & y_0 \\ 0 & 0 & 1 \end{bmatrix} \times \left[\begin{array}{ccc|c} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{array}\right] \begin{Bmatrix} X^C \\ Y^C \\ Z^C \\ 1 \end{Bmatrix} = K \begin{Bmatrix} X^C \\ Y^C \\ Z^C \\ 1 \end{Bmatrix} \tag{1}$$

Where superscript (c, i) and C represents camera image plane and camera coordinate respectively, γ is a camera sensor pixel aspect ratio, s is a sensor pixel skew, f is a focal length and (x_0, y_0) is image plane center point.

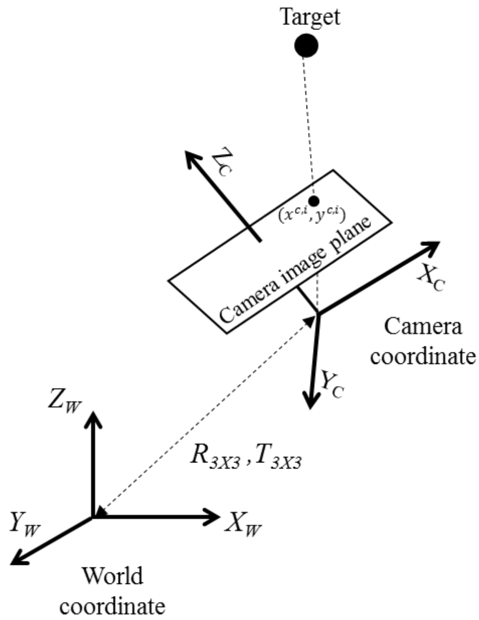

Figure 2. Coordinates in camera system

As it can be seen in Fig. 2, world coordinate and camera coordinate would be related by rotation and translation matrix as shown in equation (2).

$$\begin{Bmatrix} X^C \\ Y^C \\ Z^C \\ 1 \end{Bmatrix} = \begin{bmatrix} R^T_{3\times3} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} I_{3\times3} & -T_{3\times1} \\ 0 & 1 \end{bmatrix} \begin{Bmatrix} X^W \\ Y^W \\ Z^W \\ 1 \end{Bmatrix} \tag{2}$$

Where superscript W represents world coordinate, T is a translation vector and R is a rotation matrix. Combining equation (1) and (2) gives direct relationship between camera image plane coordinate and the world coordinate.

$$\lambda \begin{Bmatrix} x \\ y \\ 1 \end{Bmatrix} = KR_{3\times3}^{T}[\mathrm{I}_{3\times3} | -T_{3X3}] \begin{Bmatrix} X^W \\ Y^W \\ Z^W \\ 1 \end{Bmatrix} = P \begin{Bmatrix} X^W \\ Y^W \\ Z^W \\ 1 \end{Bmatrix} = PX \tag{3}$$

A matrix P in equation (3) is called camera projection matrix. This P matrix should be obtained prior to use SPR system, through camera calibration process.
Using multiple n number of cameras to take an image of the target, systems of equation is obtained.

$$\begin{bmatrix} x_1 P_{31}^T - P_{11}^T \\ y_1 P_{21}^T - P_{11}^T \\ \vdots \\ x_n P_{3n}^T - P_{1n}^T \\ y_n P_{2n}^T - P_{1n}^T \end{bmatrix} X = AX = 0 \tag{4}$$

Then the null space of A gives the 3D position of the target.

3 SIMS Framework

The simulation framework named SIMS has been developed and introduced in previous work. [6] Some important points are briefly reviewed in this paper.

3.1 Framework Overview

SIMS consists of three main parts, which are ‘structure model’, ‘camera model’ and ‘SPR algorithm model’ part. Structure model part is in charge of generate structure time-historical motion, combining structure properties and applied force. Used marker dimension and distribution is also determined in this part. Camera model part is to generate time-historical camera data. Camera intrinsic and extrinsic parameters are should be determined. Finally, SPR algorithm part is to recover structure motion monitored by defined camera system. The estimated structure motion data and original motion data are compared to evaluate the performance of designed SPR system.

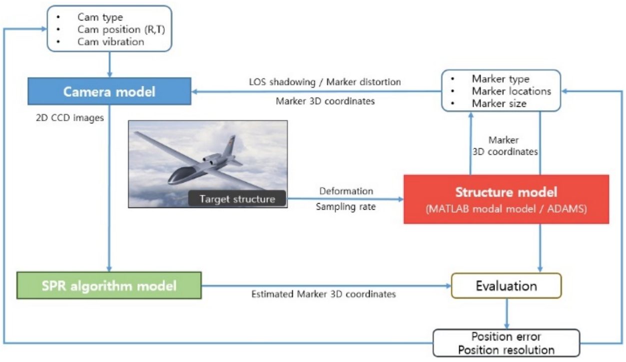

Figure 3. SIMS framework overview [6]

3.2 Error Criteria

3.3.1 Point-wise Error

By comparing two different structure motion data obtained through the simulation, error on each marker point is generated.

$$er_{\gamma}(k,t) = \widehat{H}_{\gamma}(k,t) - H_{\gamma}(k,t) \tag{5}$$

Where er_{γ} is an error on marker k at time t, $\widehat{H}_{\gamma}$ is a original structure motion and H_{γ} is a recovered motion.

3.3.2 Normalized RMS Error

To average point-wise error through the whole N marker points, Root Mean Square (RMS) error is estimated for each direction.

$$E_{RMS,\gamma}(t) = \sqrt{\frac{\{\mathrm{er}_{\gamma}(\mathrm{t})\}^T \{\mathrm{er}_{\gamma}(\mathrm{t})\}}{N}} \tag{6}$$

Then this RMS error is normalized by the maximum deformation of the structure.

$$E_{NRMS,\gamma}(t) = \frac{E_{RMS,\gamma}(t)}{\max_t(\sqrt{\{D_\gamma(t)\}^T\{D_\gamma(t)\}})} \qquad (7)$$

As a representative error to show the SPR system performance, the maximum value of Normalized RMS Error (NRE) is chosen.

4 Parameter Study Using SIMS

4.1 Target Structure

A thin and wing-shaped plate model is chosen as the target structure to be monitored. Its dimension and the material properties are summarized in table 1.

Table 1. Structure properties

Root Chord length [mm]	300
Tip Chord length [mm]	100
Span [mm]	2000
Thickness [mm]	10
Density [kg/m^3]	2770
Young's Modulus [GPa]	71.0

In the simulation, target structure vibrates with the boundary condition of clamped root, other sides free.

4.2 Structure Motion Simulated In SIMS

For the SPR camera system measurement simulation, the target structure is set to undergo defined vibrating motion. For this, modal analysis of the target structure is done, up to 8th mode using ANSYS R15.0. (table 2)

Table 2. Natural frequency of target structure

Mode number	Natural frequency [Hz]
1	2.77
2	15.16
3	36.01
4	55.12
5	68.01
6	73.92
7	118.92
8	135.27

LTI simulation model is formulated in state space form as below [8], with damping ratio has set to 2%.

$$\{\dot{x}\} = [A]\{x\} + [B]\{u\}$$
$$\{y\} = [C]\{x\} \qquad (8)$$

where $\{x\}$ is state variables in principal coordinates, $\{y\}$ is displacement of each node in physical coordinates and $\{u\}$ is the force input.

Here, six different motions are generated in SIMS structure model part. Each six vibrating motions are in resonance with the structure mode shape from 1st to 6th, induced by six sinusoidal input forces with 0.1N amplitude and structure natural frequencies.

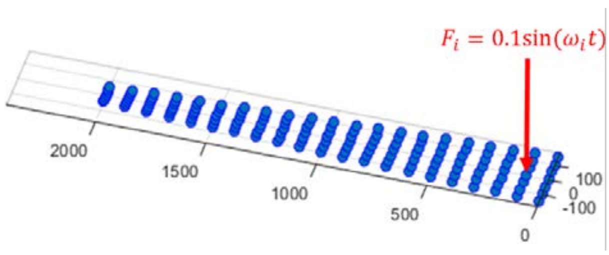

Figure 4. Simulation of target structure motion in SIMS

For each vibration cases, maximum directional deformation values are summarized in table 3.

Table 3. Maximum directional deformation

Vibration cases	X [mm]	Y [mm]	Z [mm]
Mode 1	4.80	6.71	63.58
Mode 2	5.22	9.43	122.03
Mode 3	10.10	10.77	90.13
Mode 4	18.28	20.03	156.13
Mode 5	120.98	149.01	28.31
Mode 6	5.41	7.25	163.96

4.3 SPR System Sensitivity Analysis

To study dependency of SPR system performance upon system parameter change, sensitivity analysis has performed on three camera intrinsic parameters. Those parameters are shutter speed, resolution and frame rate. As a performance indicator, z-directional maximum NRE is chosen, since deformation in z-direction is dominant except for mode 5. In the analysis, position and orientation of two cameras are fixed as in table 4.

Table 4. Camera extrinsic parameter set in spherical coordinates

		Camera 1	Camera 2
Position	R [mm]	1000	1000
	Θ [deg]	25	25
	Φ [deg]	0	0
Orientation [deg]	Rx	235	235
	Ry	-18.7	18.7
	Rz	0	0

For this camera position and orientation set up, SPR system monitor the vibration cases described in section 4.2 by varying one of the three parameter of interest. Also, fifteen markers are used to monitor structure motions. The SPR system configuration is as shown in Fig.5.

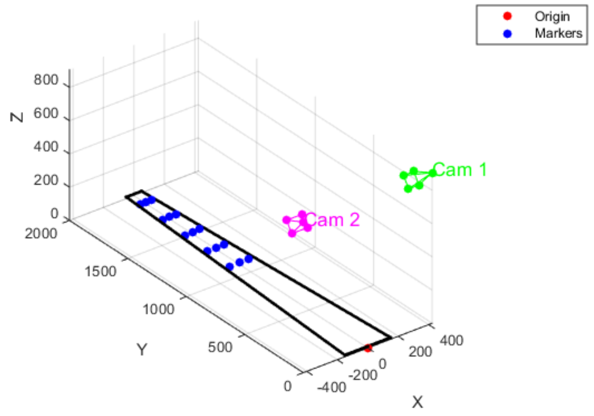

Figure 5. SPR system configuration for simulation

In addition, the SPR system performance is estimated based on maximum value of normalized RMS error as in equation (7).

4.3.1 Varying Shutter Speed

If the target structure motion is periodic motion, camera shutter speed, also known as an exposure time, should be determined considering the period of motion. For this case, only first two vibration modes are considered with varying camera shutter speed. Shutter speed is increasing from 0.5ms, bounded by 10 times of minimum vibration period. Resolution and frame rate are set to $[\mathbf{1280} \times \mathbf{1024}]$ and 240Hz, respectively. SPR system performance is measured as in table 5.

Table 5. Maximum NRE and sensitivity with respect to varying shutter speed

Shutter speed [ms]	Mode 1	Mode 2
0.5	13.73	6.68
1	13.74	6.45
2	13.77	6.25
5	13.55	5.98
Sensitivity [Max. NRE (%)/ms]	-0.04	-0.15

Sensitivity values are small, both less than 1%. This implies that change in shutter speed do not affect measurement performance if it is in reasonable range, as expected. In addition, maximum NRE values of vibration mode 2 is about the half of vibration mode 1, since the maximum deformation is double.

4.3.2 Varying Resolution

In this case, all the structure motions except mode 5 are monitored by varying both camera's resolution as in table 6.

Table 6. Resolution cases for sensitivity study

Resolution	Pixel size [mm/pixel]
64×48	9.60×10^{-2}
320×240	1.90×10^{-2}
640×480	1.00×10^{-2}
960×640	0.65×10^{-2}
1280×1024	0.48×10^{-2}
1920×1080	0.32×10^{-2}
3840×2160	0.16×10^{-2}

Frame rate and shutter speed are set to 240Hz and 1ms, respectively. The sensitivity of maximum NRE to camera resolution is summarized in Fig. 6 and table 7.

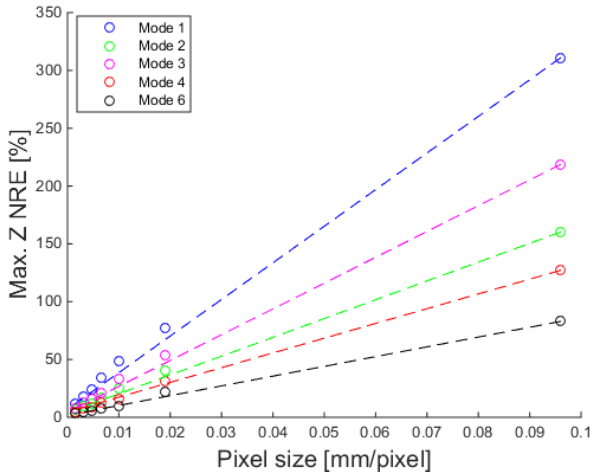

Figure 6. SPR system performance according to varying camera resolution

Clearly, maximum NRE increases linearly as pixel size is getting bigger. Sensitivity of each motion with respect to pixel size is summarized in table 7.

Table 7. SPR system performance with respect to resolution change

Structure motion	Sensitivity [Max. NRE(%)/pixel size]
Mode 1	3.17×10^{3}
Mode 2	1.63×10^{3}
Mode 3	2.23×10^{3}
Mode 4	1.29×10^{3}
Mode 6	0.84×10^{3}

Also, sensitivity value decreases as maximum deformation, which is the denominator of NRE equation, increases. This implies that measurement accuracy does not dependent on vibration motion.

4.3.3 Varying Frame Rate

By varying frame rate, SPR system performance is measure as in table 8. Vibration mode 3 and 4 are chosen for this study. Resolution and shutter speed are set to [1280×1024] and 1ms, respectively.

Table 8. Maximum NRE and sensitivity with respect to varying frame rate

Frame rate [Hz]	Mode 3	Mode 4
150	3.32	1.93
240	3.02	1.97
350	3.11	1.96
500	3.18	1.93
800	3.21	1.97
1000	3.18	1.96
Sensitivity [Max. NRE (%)/Hz]	-1.65×10^{-4}	35.29×10^{-5}

As it is obvious in max NRE values and a sensitivity, SPR system performance keep constant with change in frame rate. It is clear that frame rate does not affect the measurement accuracy, even though it is important to catch dynamic characteristics of motion.

5 Conclusion

This study presents a sensitivity analysis of SPR system in measuring structural vibration. The three camera intrinsic parameters, shutter speed, resolution and frame rate are chosen as a parameter of interest. In every three cases, sensitivity is evaluated based on z-directional maximum NRE. Sensitivities are evaluated for each parameter via simulation, with an aid of SIMS framework. With thin and tapered shape of plate as a target structure, configured SPR system monitors its vibration. Vibrating motions are set to harmonic to its mode vibration from 1st to 6th mode.

In varying shutter speed simulation, sensitivity values are around 0.1%, implies that SPR system performance is not affected by shutter speed. Same tendency is found in varying frame rate case. Sensitivity value with respect to Hz are even smaller, lower than 0.001%. However, it is found out that measurement accuracy is closely related to resolution. Maximum NRE increases linearly with increasing pixel size, which implies low resolution, for every vibration monitoring cases.

By referring this sensitivity result, SPR system intrinsic parameters can be decided in engineering sense.

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References

[1] Meng, X., Dodson, A., Roberts, G. and Cosser, E, Hybrid sensor system for bridge deformation monitoring : Interfacing with structural engineers, IUGG, Sapporo, Japan, 2003.

[2] Korayem, M. H., Shafei, A. M., and Absalan , F., Estimate a Flexible Link's Shape by the Use of Strain Gauge Sensors, *International Scholarly Research Notices*, Vol. 2013, pp.1-9, 2013.

[3] Kim, H.-I., Kang, L.-H., and Han, J.-H., Shape estimation with distributed fiber Bragg grating sensors for rotating structures, *Smart Materials and Structures*, Vol. 20, No. 3, 035011, 2011.

[4] Kim, H.-I., Kim, H.-Y., Park, H.-J., and Han, J.-H., Development of a point tracking system for measuring structural deformation using commercial video cameras, *International Journal of Aeronautical & Space Science*, Vol. 10, No.2, pp.86-94, 2009.

[5] Kim, H.-I., Han, J.-H., and Bang, H.-J., Real-time deformed shape estimation of a wind turbine blade using distributed fiber Bragg grating sensors, *Wind Energy*, Vol. 17, No. 9, pp.1455-1467, 2014.

[6] Yun, J.-M., Kim, H.-Y., Kim, H.-I., Han, J.-H., and Kwon, H.-J., Performance evaluation of homogeneous stereo camera system for full-field structural deformation estimation, *International Journal of Aeronautical and Space Science*, Vol. 16, No. 3, pp.380-393, 2015.

[7] Pang, Z. Y., Cesnik, C. E., and Atkis, E. M., In-Flight Wing Deformation Measurement System for Small Unmanned Aerial Vehicles, *55th AIAA/ASME/ASCE/AHS/SC Structures, Structural Dynamics, and Materials Conference*, National Harbor, MD, AIAA 2014-0330, 2014.

[8] Michael, R. H., *Vibration simulation using MATLAB and ANSYS*, Chapman & Hall, New York, 2001.

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