

Structural observation of long-span suspension bridges for safety assessment: implementation of an optical displacement measurement system

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Abstract. This paper addresses the implementation of an optical displacement measurement system in the observation scenario of a long-span suspension bridge and its contribution for structural safety assessment. The metrological background required for quality assurance of the measurements is described, namely, the system's intrinsic parameterization and integration in the SI dimensional traceability chain by calibration, including its measurement uncertainty assessment.

1. Introduction

Observation is an important activity in safety assessment of large structures (such as bridges, viaducts, buildings, dams, among others), contributing for their structural condition monitoring and allowing a reliable analysis of its operational performance in accordance with safety requirements and historical records, thus providing relevant information for management entities.

In the long-span suspension bridge observation context, research efforts have been geared towards the development of non-contact measurement systems, capable of determining the 3D displacement of critical regions, namely, the bridge's main span central section. Optical systems are an attractive solution for the mentioned measurement problem, particularly, for the case of metallic bridges observation, where the accuracy of microwave interferometric radar systems [1] and global navigation satellite systems [2] can be compromised, namely, by the multi-path effect resulting from electromagnetic wave reflections in the bridge's structural components.

Recently, an optical methodology suitable for long-distance measurement of suspension bridges dynamic displacement has been studied and proposed by the authors [3]. This approach is supported by the use of a digital camera rigidly installed beneath the bridge's stiffness girder, oriented towards a set of four active targets placed at a tower foundation, materializing the world referential 3D system. Provided both the camera's intrinsic parameters and the targets relative coordinates are accurately known (by previous testing), non-linear optimization methods can be used to determine the position of the camera's projection center. The temporal evolution of this quantity is considered representative of the bridge's dynamic displacement at the location of the camera.

Following the design and development stages detailed in [3], this paper describes the implementation of the system in a real observation scenario: the 25th of April long-span suspension bridge (P25A) in Lisbon (Portugal). The experimental apparatus is described and displacement results



are also presented and discussed. Special focus is given to the assurance of the metrological quality process: (i) the camera's intrinsic parameterization by the diffractive optical element method [4]; (ii) the system's field calibration, aiming its integration in the SI traceability chain; (iii) the measurement uncertainty evaluation, supported in the use of a Monte Carlo method and following the main guidelines given in the GUM-S1 supplement [5].

2. Displacement measurement in a long-span suspension bridge

In order to implement a displacement measurement system in the P25A bridge, a solution based on off-the-shelf optical components (listed in Table 1) was developed for a observation distance near 500 m. To obtain suitable 3D displacement measurement sensitivity, a 600 mm high focal length lens (composed by a 300 mm telephoto lens and a 2x teleconverter) was used.

Table 1 – Main optical components of the displacement measurement system installed in the P25A bridge

Component	Brand	Model	Technical specifications
Digital camera	IMPERX	IPX 2M30H-LM	Monochromatic CCD sensor; 1080 x 1920 pixels; 7,4 μm squared pixel
Telephoto lens	SIGMA	300 mm F2.8 EX APO DG	300 mm focal length
Teleconverter	SIGMA	2x EX APO DG	2x focal length
Optical filter	Schneider Kreuznach	B+W infrared filter 092	100% transmissivity above 730 nm wavelength
Leds	Avago Technologies	HSDL 4260	875 nm near-infrared wavelength

Figure 1 shows the set of four active targets placed in the P25A bridge south tower foundation, facing the bridge's main span where the camera was installed (Fig. 2). Each of the four targets was composed by 16 leds, distributed in a circular geometrical pattern and capable of emitting a narrow near-infrared beam (875 nm wavelength) compatible with the camera's spectral sensitivity. An optical filter on the camera reduces the environment visible irradiance from the many other elements of the observation scenario, therefore improving contrasts in the targets image (see Fig. 3).



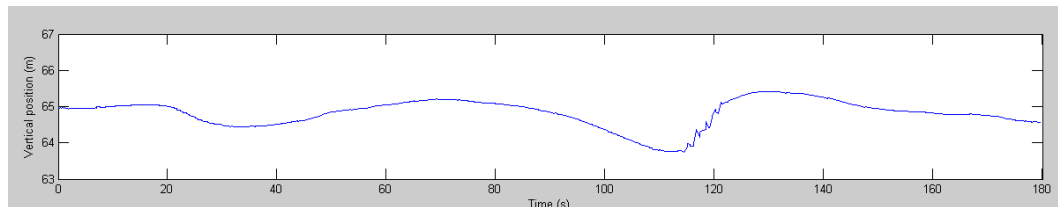
Figures 1 to 3 – Active targets on the south tower foundation (left); digital camera installed in the stiffness girder (center); detail of the image of the targets (right)

High frequency vibrations in the camera were mitigated by rubber washers and expanded polystyrene foam mounted between the camera's support structure and the stiffness girder lower surface. Other operational concerns were related to: (i) the acquisition frequency – a reference value of 15 Hz was defined, based on the image acquisition maximum capacity of the applied digital camera; (ii) the exposure time – a value of 2,5 ms was established in order to avoid image blurring due to the bridge's dynamic displacement; (iii) the lens f-number or relative aperture – this operational parameter was set to $f/5,6$, allowing a minimum amount of light in the camera's sensor (avoiding saturation) but keeping all the active targets visible. The images were processed fitting an ellipse to each visible target on the image and estimating its center.

Since the P25A bridge has two main decks (an upper road deck and a lower train deck), two types of displacement records – with and without train circulation – were obtained during field testing of the displacement measurement system. Table 2 presents the maximum (peak-to-peak) displacements for each of the studied structural scenarios. Figure 4 illustrates the vertical displacement of the bridge's main span central section. Close to $t = 120$ s, the peak detail of the steps related to the four carriage connections of the train is also noticed.

Table 2 – Maximum displacement values recorded for the P25A bridge central section during field testing

Load condition	Transverse displacement	Vertical displacement	Longitudinal displacement
With passengers train	0,39 m	1,69 m	0,07 m
Without passengers train	0,29 m	0,53 m	0,02 m

**Figure 4** – P25A bridge central section vertical displacement during passengers train circulation

As expected, the train circulation on the P25A bridge increases the 3D displacement magnitudes, namely in the vertical direction where a maximum (peak-to-peak) displacement of 1,69 m was recorded. This value is comparable to previous known vertical displacement measurements obtained during the P25A bridge static loading test performed in 1999 (after its structural reinforcement for train circulation), where a maximum vertical displacement of 3,15 m (2,37 m downward plus 0,78 upward) was recorded for a static distributed load of 77,5 kN/m. Passengers train distributed loads are usually between 20,7 kN/m (empty train situation) and 28,8 kN/m (overload train), thus originating lower vertical displacements.

3. Metrological quality assessment

3.1. Introduction

In order to evaluate the accuracy level of the displacement estimates, a metrological quality assessment was performed, following three stages: camera's intrinsic parameterization, system's field calibration and measurement uncertainty evaluation – described in detail in the following sections.

3.2. Intrinsic parameterization

Before installation in the P25A bridge, the digital camera was subjected to laboratorial testing to obtain its intrinsic parameters, namely, focal length, principal point coordinates and distortion coefficients. Being a high focal length camera (close to 600 mm), the diffractive optical element (DOE) method [4] was applied since conventional parameterization approaches, usually applied for reduced focal lengths, are not suitable because they generate ill-conditioned matrices in least squares estimation.

A collimated laser beam and a DOE were used on an optical bench to create a regular spatial distribution of diffraction dots in the camera's focal plane. Based on the accurate knowledge of the laser wavelength, DOE grating period, observed diffraction orders and centroid locations of the corresponding diffraction dots, the intrinsic parameters can be determined using only one image in a controlled laboratorial environment, considering the pinhole and 1st order radial distortion models and using non-linear optimization [6].

In order to evaluate the measurement uncertainties related to the intrinsic parameters, a Monte Carlo method study was performed following the main guidelines mentioned in [5] due to the use of a non-linear optimization procedure. In the input probabilistic formulation, the laser wavelength estimate ($632,8 \times 10^{-9}$ m) was considered constant and a Gaussian probability function was adopted for the DOE grating period quantity, centered at $152,4 \times 10^{-6}$ m with a standard measurement uncertainty of $0,15 \times 10^{-6}$ m. Based on the digital image processing performances, a standard measurement uncertainty of $p/4$ (where p is pixel size) was assigned to the diffraction image coordinates estimates. Results are presented in Table 3. They are supported in 10 000 Monte Carlo runs, for which a computational

accuracy level of 0,1 mm (for the focal length quantity) and 0,01 pixel (for principal point coordinates) were achieved.

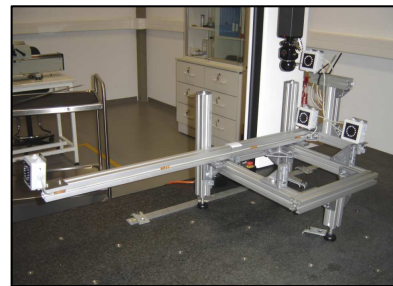
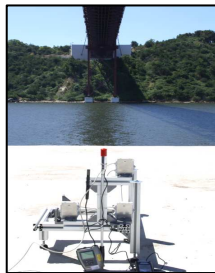
Table 3 – Estimates, measurement expanded uncertainties and correlation coefficients obtained from Monte Carlo simulations

Focal length		Principal point x-coordinate		Principal point y-coordinate	
Average value (mm)	95% expanded uncertainty (mm)	Average value (pixel)	95% expanded uncertainty (pixel)	Average value (pixel)	95% expanded uncertainty (pixel)
599,95	0,75	545,61	0,06	960,41	0,09
Correlation coefficients					
Focal length / Principal point x-coordinate: -0,28					
Focal length / Principal point y-coordinate: -0,35					
Principal point x-coordinate / Principal point y-coordinate: -0,25					

The intrinsic parameters estimates for focal length and principal point coordinates are close to the corresponding nominal values (600 mm, 540 pixel and 960 pixel). As expected for high focal length lenses, the estimate for the first-order coefficient of radial distortion is residual and, therefore, is considered to be insufficient to affect image coordinates due to image processing performances. Radial distortion is, consequently, irrelevant and the distortion model can be removed from optimization, both in the parameterization and in displacement measurement procedures.

3.3. Dimensional traceability

Dimensional traceability of the optical measurement system was achieved by a field calibration test performed at the P25A bridge, where both the camera and the set of targets were placed, respectively, in the bridge's south anchorage and in the south tower foundation (Figure 5). When compared with the bridge's central section, these two regions have shown reduced dynamics and can be considered nearly static regions, allowing establishing a line of sight symmetric to the measurement line of sight between the central section and the south tower foundation – the camera remaining, approximately, at the same altitude for both geometrical configurations.



Figures 5 and 6 – Calibration field test and laboratorial dimensional testing of the calibration device prototype

The calibration method proposed implies the acquisition of images of the set of targets supported by known 3D reference positions in the bridge's main displacement directions (vertical, transverse and longitudinal). The system's measurement model can be applied to each image, allowing to know the camera's projection center virtual displacement between two images (the initial and final targets position) which can be compared with the reference displacement initially applied to the set of targets. In order to implement this calibration method, a dedicated device prototype (shown in Figures 5 and 6) was developed for the installation of the set of targets and application of reference displacement in the bridge's main displacement directions.

A SI traceable 3D coordinate measuring machine¹ was used to determine the spatial coordinates of the targets LED's in all four reference positions (initial position, 250 mm in the longitudinal direction,

¹ The same standard equipment was also used for dimensional testing of the targets world coordinates (relative to one of the targets) required for the displacement measurement process.

350 mm in the transverse direction and 250 mm in the vertical direction) in order to obtain reference displacement estimates. Table 4 shows the reference and measured displacement values and corresponding deviations obtained in the field calibration test.

Table 4 – Field calibration results

	Transverse displacement			Vertical displacement			Longitudinal displacement		
	Measured value (mm)	Reference value (mm)	Deviation (mm)	Measured value (mm)	Reference value (mm)	Deviation (mm)	Measured value (mm)	Reference value (mm)	Deviation (mm)
X	-349,9	-350,6	0,7	-2,0	-0,8	-1,2	0,3	-0,4	0,7
Y	1,5	0,1	1,4	-251,0	251,3	0,3	1,7	0,5	1,2
Z	0,0	-0,1	0,1	0,0	0,0	0,0	250,0	251,5	-1,5

The analysis of the values in the previous Table shows that the maximum calibration deviations in each displacement direction is between -1,5 mm and 1,4 mm. It should also be mentioned that, if vertical refraction corrections are applied to targets world coordinates [7], the vertical deviation presented in the vertical displacement test (0,3 mm) becomes null, thus improving its accuracy.

3.4. Measurement uncertainty evaluation

The measurement uncertainty evaluation was performed in order to estimate the dispersion of values related to the calibration deviations mentioned in section 3.3, aiming to quantify the accuracy level of the optical displacement measurement system.

In a probabilistic approach, the measurement uncertainty related to the calibration deviation combines the dispersions of values assigned to the reference displacement and the initial and final positions of the camera projection center.

Regarding the reference displacement, the following uncertainty components were quantified: (i) the measurement of the initial and final target position, which combines both the instrumental uncertainty of the 3D coordinate measurement machine and the circularity deviation obtained in the measurement of the geometrical pattern of the targets; (ii) the return to zero deviation when the referential returns to the initial position; (iii) the differential displacement between pairs of targets; (iv) the repeatability related to the operational method of mounting the set of targets in the calibration device.

The initial and final position of the camera projection center combines the measurement uncertainties of the following input quantities: (i) the focal length and principal point quantities, as mentioned in 3.2; (ii) the targets image coordinates which, in turn, combine the measurement uncertainties related to the digital image processing and turbulence due to thermal vertical gradients; beam wandering tests performed at the P25A bridge (in a similar way as described for the field calibration test in section 3.3 but without moving the set of targets) revealed that this uncertainty component changes between 0,13 pixel (in the winter, with shadow over the targets) and 0,56 pixel (in the summer, without shadows over the targets); (iii) the targets world coordinates which include the uncertainty contributions related to: the laboratorial dimensional measurement; the target circularity; the environmental temperature influence to the set of targets on the P25A bridge; the transport and assembly of the set of targets in the tower foundation; the vertical refraction correction.

Due to the non-linear optimization procedure when determining the camera's projection center position, a Monte Carlo method was used for the propagation of measurement uncertainties of the input quantities previously referred to the output quantities measurement uncertainties. This method is particularly suitable since this multivariable process implies performing several iterations, making difficult to apply other approaches, namely, the conventional ISO-GUM method. In addition, it allows knowing the shape of the output probability density functions and the optimization process stability. Table 5 summarizes the results based on 10000 simulation runs.

Table 5 –Measurement standard uncertainties of input, intermediate and output quantities

INPUT QUANTITIES	Camera's intrinsic parameters		Target world coordinates	
	Focal length, f	$0,38 \cdot 10^{-3}$ m	Transverse direction (X)	$0,57 \cdot 10^{-3}$ m
	Principal point x-coordinate, u_0	0,030 pixel	Vertical direction (Y)	$0,69 \cdot 10^{-3}$ m
	Principal point y-coordinate, v_0	0,045 pixel	Longitudinal direction (Z)	$0,36 \cdot 10^{-3}$ m
	Correlation coefficient (f, u_0)	-0,28	Target image coordinates	
	Correlation coefficient (f, v_0)	-0,35	x-coordinate	0,13 pixel
	Correlation coefficient (u_0, v_0)	-0,25	y-coordinate	0,13 pixel
	Reference displacement	Transverse displacement	Vertical displacement	Longitudinal displacement
	Transverse direction (X)	$0,97 \cdot 10^{-3}$ m	$0,58 \cdot 10^{-3}$ m	$0,59 \cdot 10^{-3}$ m
	Vertical direction (Y)	$0,91 \cdot 10^{-3}$ m	$0,58 \cdot 10^{-3}$ m	$0,51 \cdot 10^{-3}$ m
	Longitudinal direction (Z)	$0,90 \cdot 10^{-3}$ m	$0,47 \cdot 10^{-3}$ m	$0,45 \cdot 10^{-3}$ m
INTERMEDIATE QUANTITIES	Camera initial position	Transverse displacement	Vertical displacement	Longitudinal displacement
	Transverse direction (X)	$0,95 \cdot 10^{-3}$ m	$0,95 \cdot 10^{-3}$ m	$0,95 \cdot 10^{-3}$ m
	Vertical direction (Y)	$0,95 \cdot 10^{-3}$ m	$0,95 \cdot 10^{-3}$ m	$0,95 \cdot 10^{-3}$ m
	Longitudinal direction (Z)	$8,5 \cdot 10^{-3}$ m	$8,5 \cdot 10^{-3}$ m	$8,5 \cdot 10^{-3}$ m
	Camera final position	Transverse displacement	Vertical displacement	Longitudinal displacement
	Transverse direction (X)	$1,0 \cdot 10^{-3}$ m	$1,0 \cdot 10^{-3}$ m	$1,0 \cdot 10^{-3}$ m
	Vertical direction (Y)	$0,95 \cdot 10^{-3}$ m	$0,95 \cdot 10^{-3}$ m	$0,95 \cdot 10^{-3}$ m
	Longitudinal direction (Z)	$9,0 \cdot 10^{-3}$ m	$9,0 \cdot 10^{-3}$ m	$9,0 \cdot 10^{-3}$ m
OUTPUT QUANTITIES	Calibration deviation	Transverse displacement	Vertical displacement	Longitudinal displacement
	Transverse direction (X)	$1,7 \cdot 10^{-3}$ m	$1,5 \cdot 10^{-3}$ m	$1,5 \cdot 10^{-3}$ m
	Vertical direction (Y)	$1,7 \cdot 10^{-3}$ m	$1,4 \cdot 10^{-3}$ m	$1,4 \cdot 10^{-3}$ m
	Longitudinal direction (Z)	$13 \cdot 10^{-3}$ m	$13 \cdot 10^{-3}$ m	$13 \cdot 10^{-3}$ m

The analysis of the results shows that, for all the calibration directions, the measurement standard uncertainty related to the longitudinal direction (13 mm) is significantly higher than for the other two orthogonal directions (vertical and transverse) where a maximum value of 1,7 mm is reached. This difference can be justified by the geometrical configuration of the optical measurement system which has reduced sensitivity for the longitudinal direction.

It should be noticed that the system's field calibration was performed during winter, being the standard uncertainty of the targets image coordinates relatively low (about 0,13 pixel) when comparing with summer conditions where previous field tests showed a higher dispersion (close to 0,6 pixel). In this case, the measurement uncertainty can be increased by a multiplicative factor of 1,5 up to 2,2 in all displacement directions.

4. Conclusions

The system's implementation on the P25A bridge allowed to estimate its central section 3D displacement considering different loading scenarios, namely, due to train circulation where a maximum (peak-to-peak) vertical displacement value of 1,69 m was recorded, being consistent with historical values obtained during static loading tests performed in 1999.

Quality assurance of the obtained displacement estimates was demonstrated by uncertainty evaluation which encompasses system's intrinsic parameters, dimensional testing and field calibration. A 1,7 mm standard measurement uncertainty was calculated for the vertical and transverse calibration deviations while, in the longitudinal direction, a value of 13 mm was obtained. The Monte Carlo method was particularly suitable for the measurement uncertainty evaluation considering that the measurement procedure includes an iterative multivariable non-linear optimization.

References

- [1] Pasquale G, Bernardini G, Ricci P, Gentile C, 2010 *IEEE Aerospace and Electronics Systems Magazine* **25**, 19-26
- [2] Nakamura S, 2000 *Journal of Structural Engineering* **126**, 1413-1419
- [3] Martins L, Rebordão J M, Ribeiro A, 2013 *Journal of Physics: Conference Series* **459**, 012055
- [4] Bauer M, Griebßbach D, Hermerschmidt A, Krüger S, Scheele M, Schischmanow A, 2008 *Optics Express* **16**, 20241-20248
- [5] *Supplement 1 to the Guide to the expression of Uncertainty in Measurement (S1 GUM)*, Joint Committee for Guides in Metrology, 2008
- [6] Lagarias J, Reeds J, Wright M, Wright P, 1998 *SIAM Journal of Optimization* **9**, 112-147
- [7] Martins L, Rebordão J M, Ribeiro A, 2014 *International Journal of Thermophysics* **34**, 5