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Bringing optical metrology to testing and inspection activities in civil engineering

Luís Martins[1], Álvaro Ribeiro[1], Maria do Céu Almeida[1], João Alves e Sousa[2]

[1] *LNEC - National Laboratory for Civil Engineering, Avenida do Brasil 101, 1700-066 Lisbon, Portugal*
[2] *IPQ - Portuguese Institute for Quality, Rua António Gião 2, 2829-513 Caparica, Portugal*

ABSTRACT
Optical metrology has an increasing impact on observation and experimental activities in Civil Engineering, contributing to the Research and development of innovative, non-invasive techniques applied in testing and inspection of infrastructures and construction materials to ensure safety and quality of life. Advances in specific applications are presented in the paper, highlighting the application cases carried out by LNEC (the Portuguese National Laboratory for Civil Engineering).
The examples include: (i) structural monitoring of a long-span suspension bridge; (ii) use of close circuit television (CCTV) cameras in drain and sewer inspection; (iii) calibration of a large-scale seismic shaking table with laser interferometry; (iv) destructive mechanical testing of masonry specimens.
Current and future research work in this field is emphasized in the final section. Examples given are related to the use of Moiré techniques for digital modelling of reduced-scale hydraulic surfaces and to the use of laser interferometry for calibration of strain measurement standard for the geometrical evaluation of concrete testing machines.

Section: RESEARCH PAPER

Keywords: Optical metrology; civil engineering; testing; inspection

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Corresponding author: Luís Martins, e-mail: lfmartins@lnec.pt

1. INTRODUCTION

Optical Metrology has a large scientific and technological scope of application, providing a wide range of measurement methods, from interferometry to photometry, radiometry and, more recently, to applications using digital, video and vision systems, which combined with computational algorithms, allow obtaining traceable and accurate measurements. Increasing accuracy of optical measurement instruments creates new opportunities for applications in Civil Engineering, namely, for testing and inspection activities.

These new methodologies open broader possibilities in Civil Engineering domains where dimensional and geometrical quantities are major sources of information on infrastructures and construction materials. The assessment of their performance and behaviour, often involves monitoring and analysis under dynamic regimes [1], [2]. In many cases, the development of new technologies, based on the use of methods combining optics and digital algorithms, have recognized advantages, namely, those using non-invasive techniques in harsh environments and remote observation [3]. Moreover, the need for accurate measurements related to infrastructures management, e.g., in early detection of damage or in safety monitoring, is growing. The contribution of Metrology in this area is key to increase the confidence in decision-making processes.

R&DI activities in the Optical Metrology domain in recent years at the Portuguese National Laboratory for Civil Engineering (LNEC) led to the development of innovative applications, many of them related to doctoral academic research. The main objectives are: (i) to design and develop optical solutions for applications where conventional instrumentation does not provide satisfactory results; (ii) to establish SI (International System of units) traceability of measurements undertaken with optical instruments; (iii) to develop advanced mathematical and numerical tools, namely based on Monte Carlo methods (MCM) and Bayesian methods, bringing benefits to the evaluation of measurement uncertainty in complex and non-linear optical problems.

This paper exemplifies how new methods enable traceable and accurate solutions to assess conformity with safety requirements, providing support to the measurement uncertainty evaluation as a tool to use decision rules. In addition, the applications described emphasize the role of digital and optical systems, as a basis for robust techniques able to provide measurement estimates for dimensional quantities, replacing conventional invasive measurement approaches. To illustrate these achievements, results of R&DI in the Civil Engineering context are presented, including examples of application in: (i) structural monitoring of a long-span suspension bridge; (ii) drain and sewer inspection using CCTV cameras; (iii) calibration of a large-scale seismic shaking table with laser interferometry; (iv) destructive testing of masonry specimens.

2. OVERVIEW OF OPTICAL METROLOGY

Optical Metrology is a specific scientific area of Metrology, defined as *the science of measurement and its applications* [4], in which experimental measurement processes are supported by light. Currently, it has a significant contribution in multiple scientific and engineering domains, improving measurement methods and instruments, to assess their limits and increasing their capabilities in order to improve the knowledge of the studied phenomena.

In recent years, the technological development of computational tools has extended the Optical Metrology activity scope, by increasing the number of measurement processes supported in digital processing of images obtained from optical systems [5]. This activity is characterized by the detection and record abilities, without physical contact with the object and in minor time interval, of a large amount of information (dimensional, geometrical, radiometric, photometric, colour, thermal, among others), overcoming human vision limitations, reaching information imperceptible for human eyes and, therefore, improving knowledge about phenomena.

Although this paper is focused on dimensional measurements, Optical Metrology also reaches other domains of activity, namely, temperature, mechanical and chemical quantities. Optical Metrology covers a wide range of dimensional measurement intervals, from nanometer magnitude up to the dimension of celestial bodies and space distances. In this context, measurement principles are usually grouped in three categories [6]:

(i) geometrical optics – related to the refraction, reflection and linear propagation of light phenomena, which are the functional support of several instruments and measurement systems composed by light sources, lenses, diaphragms, mirrors, prisms, beam splitters, filters and optical electronic components;

(ii) wave optics – where the wave nature of light is explored, namely, the interference of electromagnetic waves with similar or identical wavelength, being present in a wide range of instruments and measurement systems which use polarized and holographic optical components and diffraction gratings; and

(iii) quantum optics – supports the generation of laser beams which correspond to high intensity and monochromatic coherent light sources used, e.g., in sub-nanometer interferometry and scanning microscopy.

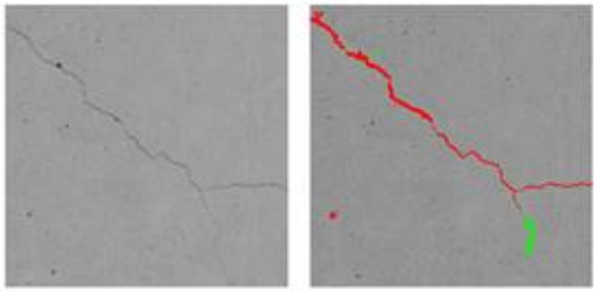

Figure 1. Digital image processing of concrete wall surface image showing crack.

In the case of Civil Engineering, two main areas for applications of Optical Metrology are identified: space and aerial observation; and terrestrial observation.

Space observation, supported by optical systems, equipped with panchromatic and multi-spectral sensors integrated in Remote Sensing satellites, is gradually more frequent in the context of Civil Engineering, due to the growing access to temporal and spatial collections of digital images of the Earth's surface with increasing spatial resolution.

Aerial observation is generally focused on photogrammetric activities undertaken from aircrafts, aiming at the production of geographic information to be included in topographic charts or geographical information systems, namely, through orthophotos and three-dimensional models (realistic or graphical) representing a certain region of the Earth's surface. Moreover, optical systems are also installed in UAV - Unmanned Aerial Vehicles, used in the visual inspection of large constructions, contributing to the detection and mapping of observations (e.g. cracks, infiltrations, among others) and analysis of their progression with time (see example in Figure 1) [7].

3. STRUCTURAL MONITORING OF A LONG-SPAN SUSPENSION BRIDGE

Optical Metrology has been successively applied by LNEC to the monitoring of a long-span suspension bridge, allowing the development of non-contact measurement systems, capable of determining three-dimensional displacements of critical regions, namely, in the bridge's main span central section. Optical systems are an interesting solution for this class of measurement problems, especially in the observation of metallic bridges, where the accuracy of microwave interferometric radar systems [8] and global navigation satellite systems [9], [10] can be affected, for instance, by the multi-path effect resulting from electromagnetic wave reflections in the bridge's structural components.

The measurement approach developed consists in 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 three-dimensional system. Provided that the camera's intrinsic parameters (focal length, principal point coordinates and lens distortion coefficients) 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 centre. The temporal evolution of this quantity is considered representative of the bridge's dynamic displacement at the location of the camera.

Since distances can be quite high in this type of observation context, thus the use of high focal length lenses is required to

Figure 2. Active targets on the south tower foundation.

achieve a suitable spatial image resolution. However, conventional camera parameterization methods were mainly developed for small focal length cameras (below 100 mm). When applied to high focal length cameras, such methods can reveal numeric instability related to over-parameterization and ill-conditioned matrices. A suitable solution for this problem is found in [11], where the intrinsic parametrization method is described, supported in the use of diffractive optical elements (DOE).

This approach was implemented in the 25th of April long-span suspension bridge (P25A) in Lisbon (Portugal), for an observation distance near 500 m. To obtain suitable sensitivity of three-dimensional displacement measurement, a 600 mm high focal length lens (composed by a 300 mm telephoto lens and a 2x teleconverter) was used. A set of four active targets was placed in the P25A bridge south tower foundation (Figure 2), facing the bridge's main span where the camera was installed (Figure 3).

Each of the four targets was composed by 16 leds, distributed in a circular geometrical pattern capable of emitting a narrow near-infrared beam (875 nm wavelength) and compatible with the camera's spectral sensitivity. An optical filter on the camera reduced the environment visible irradiance from many other elements in the observation scenario, thus improving contrast in the target image.

Several field validation tests were performed, aiming at the quantification of the optical phenomena influence, such as atmospheric refraction and turbulence in the dimensional measurement accuracy. A calibration device was used for this purpose [11], [12], allowing to install the set of targets in four reference positions. By placing the camera in the P25A south anchorage, orientated toward the calibration device in the P25A south tower foundation (both considered static structural

Figure 3. Digital camera installed in the stiffness girder.

regions), the systematic effect caused by refraction and the beam wandering effect originated turbulence, mainly in the Summer season, were quantified as explained in [12].

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. Due to the reduced measurement sensitivity in the longitudinal direction, demonstrated in the validation tests, only transverse and vertical displacements were recorded. An image acquisition frequency of 15 Hz was defined for an observation time interval of three minutes. The collected image sequences were digitally processed afterward, using the same techniques applied in the validation tests. Figure 4 exemplifies a typical displacement record obtained for a passengers train passage on the P25A main span central section.

For the operational condition mentioned - train and road traffic - the observed maximum (peak-to-peak) displacement were 0.39 m and 1.69 m, respectively, in the transverse and vertical directions. High-measurement sensitivity is noticed in the vertical displacement record where the number of train carriages (four) can be temporally discriminated - four small spikes around t = 120 s, with a 95 % expanded measurement uncertainty of 8.8 mm.

The distributed passengers train load was estimated between 20.7 kN/m (empty train) and 28.8 kN/m (overload train), which is considerably lower than the distributed load applied in the P25A static loading test performed in 1999, where a 3.15 m vertical displacement value was recorded for a 77.5 kN/m distributed load. As expected, in the absence of train circulation in the P25A, the observed maximum displacements were less significant, namely 0.53 m and 0.29 m, respectively, for the vertical and transverse directions, as shown in Figure 5.

4. DRAIN AND SEWER INSPECTION USING CCTV CAMERAS

Another recent example of the application of Optical Metrology to the Civil Engineering inspection context is the study carried out on the metrological quality of dimensional measurements based on images from CCTV inspections in drain and sewer systems (example shown in Figure 6).

In this context, investigations are carried out using several sources of information, including external and internal inspection activities for the detection and characterization of anomalies which can negatively affect the performance of the drain or sewer system. CCTV inspection is a largely used visual inspection technique for non-man entry components.

This type of indirect visual inspection is characterized by the quantification of a significant number of absolute and relative dimensional quantities, which contribute to the characterization of the inspection observations and, consequently, to the analysis of the performance of drain and sewer systems outside buildings. Unfavourable environmental factors and conditions in the drain or sewer components pose difficulties in the estimation of the quantities of interest and the quality of the recorded images can be quite poor (lighting, lack of reference points, geometric irregularities and subjective assessments, among others).

The study [14] stresses the need of proper metrological characterization of the optical system - the CCTV camera - used in drain or sewer inspections, namely, the geometrical characterization and quantification of intrinsic parameters using traceable reference dimensional patterns and applying known algorithms. The standard radiometric characterization, aiming at

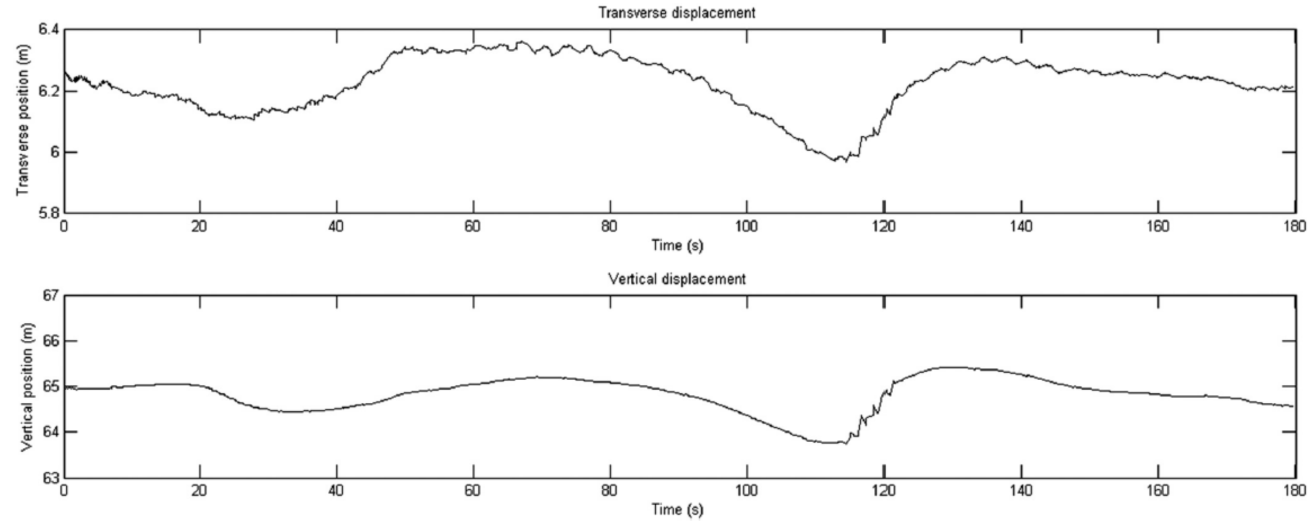

Figure 4. P25A main span central section displacement - train and road traffic.

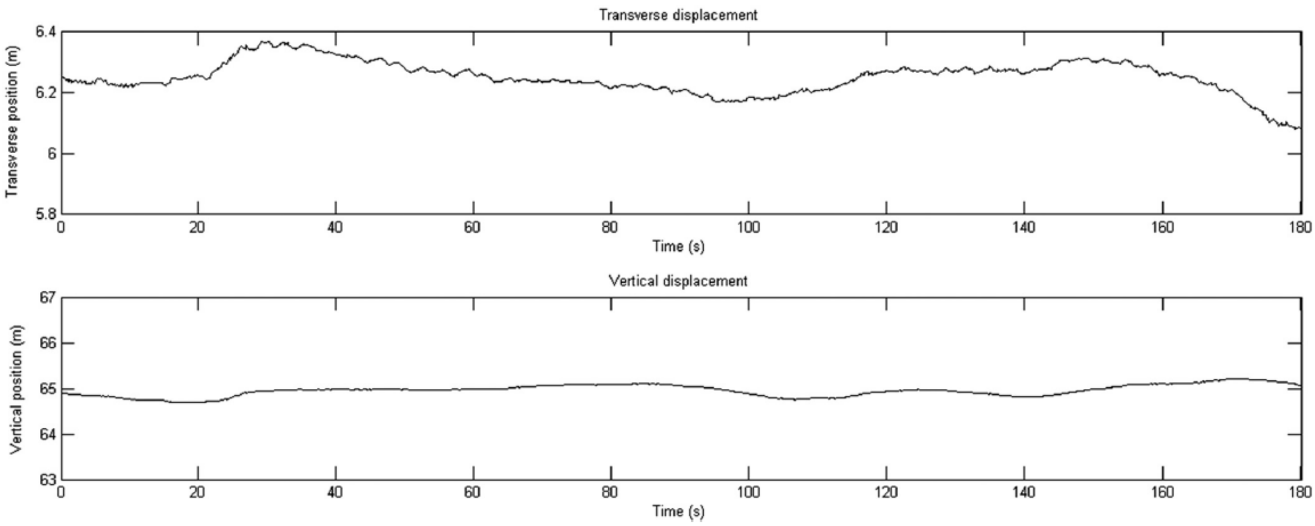

Figure 5. P25A main span central section displacement - road traffic only.

the determination of the CCTV camera sensitivity, linearity, noise, dark current, spatial non-uniformity and defecting pixels, is also mentioned [15].

Two measurement models were studied to be applied in this context - the perspective camera model and the orthographic projection camera model [16]. The first model implies having input knowledge about the camera's intrinsic parameters and the extrinsic parameters (the camera position and orientation in the local or global coordinate system), which must be obtained from instrumentation of the CCTV camera. The second model is a less rigorous approach that can be followed, assuming a parallel geometrical relation between the image plane and the cross-section plane in the drain or sewer to define a scale coefficient between real dimension (in millimetres) and image dimension (in pixels).

Research efforts were directed towards the evaluation of the measurement uncertainty following the GUM framework [17], [18]. Particular attention was given to the influence of lens distortion in the results obtained from the perspective camera model. In a typical inspection of a drain or sewer system, a reduced focal distance lens is generally used to have a wider angle. In this type of lens, distortion can cause geometrical

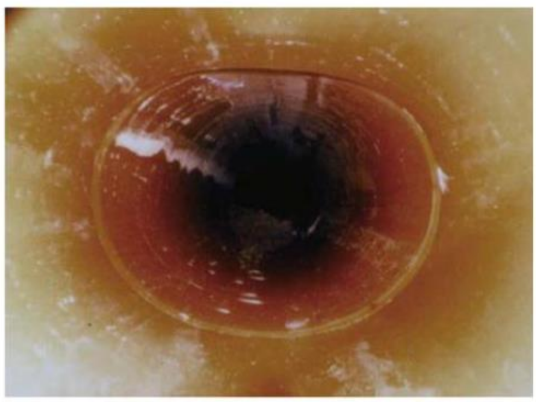

Figure 6. Inspection image showing dimensional reduction by deformation effect [13].

deformation of the image, thus affecting the accuracy of dimensional measurements.

For this purpose, intrinsic parameters' estimates and standard uncertainties were obtained [14] for the case of a camera with a 4 mm nominal focal length and an image sensor with 480 × 640 squared pixels, considering a pixel linear dimension equal to 6.5 µm. High-order radial distortion coefficients were considered negligible. The standard uncertainty related to the image coordinates, resulting from the performed intrinsic parametrization, was equal to 0.04 pixel.

To assess the impact of distortion in the image coordinate measurement accuracy, a Monte Carlo method [18] was used, given the complex and non-linear lens distortion model [19]. Figure 7 shows the estimates of the image variation due to the combined effect of radial and tangential distortions and Figure 8 presents the corresponding 95 % measurement uncertainty.

As shown in Figure 7 and Figure 8, the distortion impact in the images coordinates is quite low. As expected, a higher distortion is observed in the extreme regions of the image, especially in the corners. The maximum distortion estimate is close to 0.050 pixel with a 95 % expanded uncertainty of 0.001 pixel. These results allow to remove the distortion component from the perspective camera model, making it less complex and numerically more stable.

Due to the non-linear and complex mathematical models related to the perspective camera model, a Monte Carlo method was again applied in numerical simulation, in order to obtain the dispersion of values related to the local dimensional coordinates

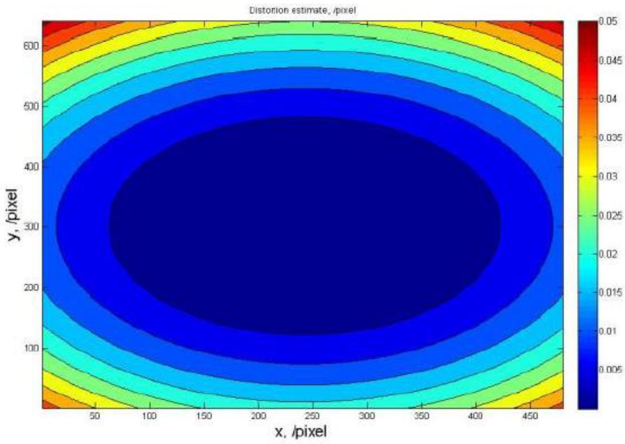

Figure 7. Image distortion estimates in pixels.

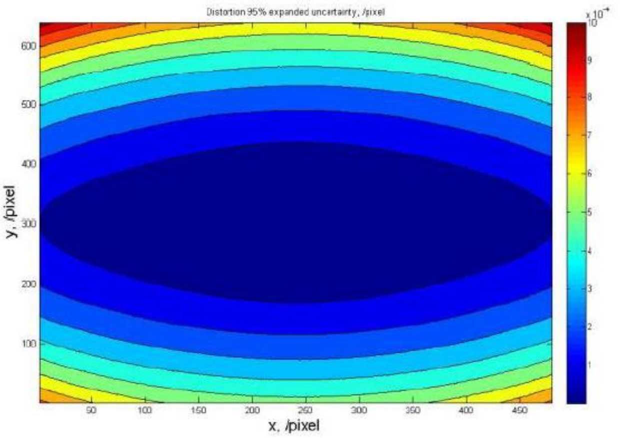

Figure 8. Image distortion 95 % expanded uncertainties in pixels.

which support dimensional measurement in inspection images. A 95 % computational accuracy level lower than 1 mm was obtained.

The simulation results showed that a dimensional accuracy level lower than 10 mm can only be achieved for a camera and plane location standard uncertainties of 1 mm and an image coordinate standard uncertainty bellow 3 pixels. In a sensitivity point of view, the camera and plane standard uncertainty showed a stronger contribution to the dimensional accuracy level, rather than the image coordinate measurement uncertainty. When compared with the global dimensions of the corresponding camera field-of-view (974 mm x 731 mm), the 95 % expanded uncertainty of the dimensional coordinates is comprised between 0.2 % and 4.1 %.

The measurement uncertainty related to the adoption of the orthographic projection model was also studied in [14] using the Uncertainty Propagation Law [17], considering the linearity of the applied mathematical models. For the worst case, related to the scale coefficient with the highest measurement uncertainty, the obtained dimensional measurement accuracy was always above 5 %. Better accuracy levels are possible, namely, in the case of the lowest measurement uncertainty of the scale coefficient, for standard uncertainties of 1.3 pixel (for dimensional measurements close to 100 mm) and 2.5 pixels (for dimensional measurements of 200 mm),

5. CALIBRATION OF A LARGE-SCALE SEISMIC SHAKING TABLE WITH LASER INTERFEROMETRY

Laser interferometry was applied for the calibration of a large-scale seismic shaking table, used by LNEC's Earthquake Engineering Research Centre in R&DI activities related to seismic risk analysis and experimental and analytical dynamic modelling of structures, components and equipment.

This European Seismic Engineering Research Infrastructure (shown in Figure 9) is composed by a high stiffness testing platform with 4.6 m x 5.6 m dimensions and a maximum payload capacity of 392 kN, connected to hydraulic actuators, allowing to test real or reduced-scale models up to extreme collapse conditions, between 0 Hz and 40 Hz [20].

The control system used allows the active application of the displacement to the testing platform in three independent orthogonal axis, while its rotation is passively restricted using torsion bars.

The performed calibration is included in the introduction of Quality Management Systems in large experimental infrastructures with R&DI [21], aiming the recognition of technical competence for testing and measurement and the formal definition of management processes, which can be regularly assessed by an independent entity. The compliance with metrological requirements is a key issue in this context, being related, for example, with traceability and calibration procedures, conformity assessment, measurement correction and uncertainty evaluation, data record management and data analysis procedures.

Laser interferometry was used to evaluate the dimensional cross-axis motion, as well as the rotation motion across axis performances of LNEC's shaking table, using specific experimental setups and optical components, as shown in Figure 10 and Figure 11.

This experimental work allowed performing remote and non-invasive measurements with a high accuracy level in a harsh environment, being composed by two stages: the laser beam

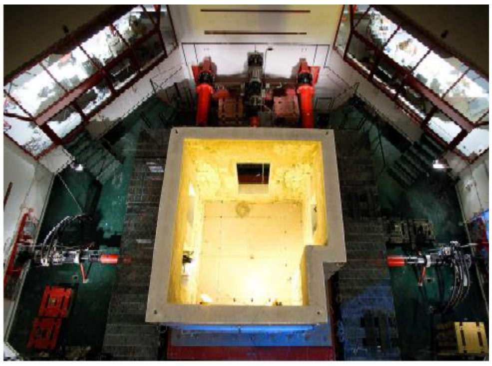

Figure 9. Top view of LNEC's Earthquake Engineering testing room [22].

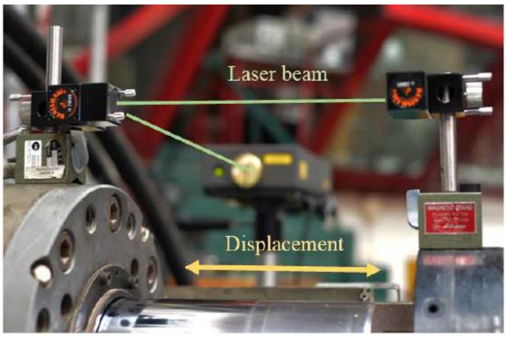

Figure 10. Experimental setup for cross-axis motion testing.

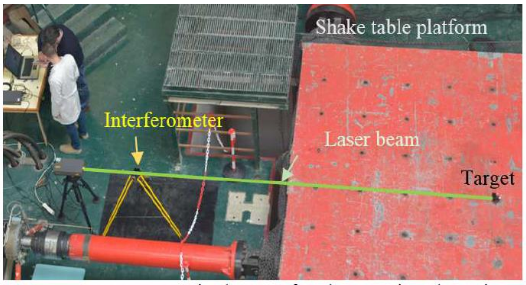

Figure 11. Experimental setup for rotation motion testing.

alignment and data acquisition (500 sampling pairs from both the interferometer and the dimensional sensors of the seismic shaking table, having a Gaussian representation of the probability distribution).

The main identified uncertainty components were related to misalignment of optical elements, time synchronization and influence quantities such as air and material temperature, relative humidity and atmospheric pressure. Specific actions were taken in order to minimize these uncertainty components, namely, full-range preliminary tests with adaptative adjustment of the main optical components, the application of a signal synchronization procedure and the use of compensation algorithms for the correction of the material thermal expansion and of the air refraction index [23].

One of the developed tests was defined in order to evaluate the dimensional scale calibration errors and reversibility, using input dynamic series with low variance 30 mm calibration steps, within a measurement interval of ± 120 mm. Examples of obtained results are shown in Figure 12 and Figure 13.

A measurement discrimination test was also developed, considering transition steps of 0.5 mm, 0.1 mm and 5.0 mm given at 20 mm, 50 mm and 80 mm linear positions. An example of the obtained results is shown in Figure 14.

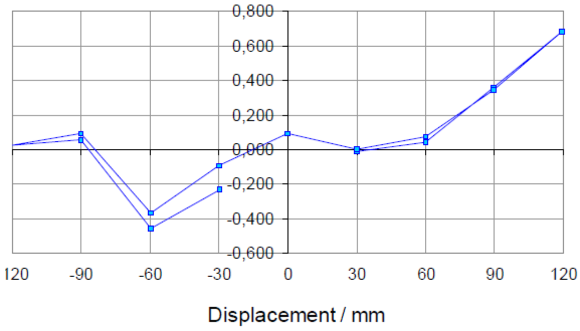

Figure 12. Calibration errors and reversibility for the static position test of axis 1-T-A.

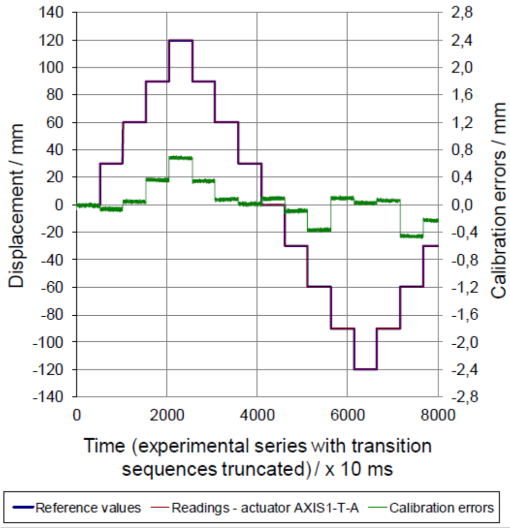

Figure 13. Calibration errors for the dynamic position test of axis 1-T-A.

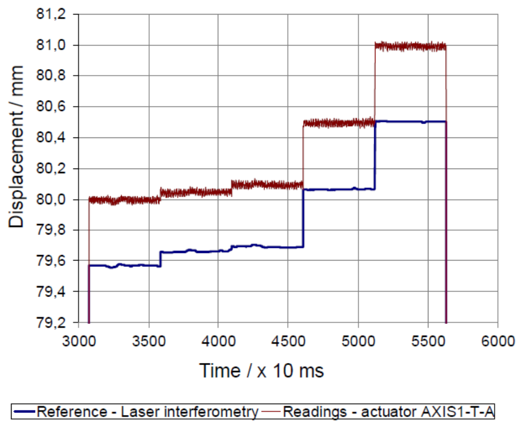

Figure 14. Results of the discrimination test of axis 1-T-A at the 80 mm position.

The obtained results show calibration errors ranging, approximately between -0.4 mm and 0.7 mm, with a reduced reversibility close to 0.1 mm. These results were included in the measurement uncertainty evaluation, from which an instrumental measurement accuracy of 0.31 mm was obtained considering a confidence interval of 95 %. The corresponding target instrumental measurement uncertainty, defined as a metrological requirement for the seismic shaking table, is equal to 1 mm.

Additional dynamical tests and the corresponding discussion of results can be found in [21].

6. DESTRUCTIVE MECHANICAL TESTING OF MASONRY SPECIMENS

The application of Optical Metrology to the destructive mechanical testing of masonry specimens was motivated by the possibility of obtaining non-contact dimensional measurements. In a destructive test, the use of classical invasive instrumentation, such as deformeters, electrical strain gauges and contact displacement sensors, is considered not suitable for some applications due to dynamic effect in the experimental setup and to the high risk of damaging the equipment.

Knowledge of mechanical characteristics of resistant masonry walls is one of the aspects that still have gaps, mainly due to the difficulty in obtaining representative specimens. In addition, the growing interest in the rehabilitation of old buildings contributes to the search for new reinforcement solutions that are compatible with the original building construction techniques [24], [25]. It is equally important to ensure that these reinforcement techniques, in addition to the aesthetic and functional aspects, also reduce the seismic vulnerability of these buildings [26].

From an experimental point view, dimensional measurements have a strong contribution for the determination of key mechanical characteristics since they support the indirect strain measurement in the tested specimens [27], [28]. Afterwards, these measurements are used for characterizing the masonry specimen mechanical behaviour in terms of its elasticity modulus and Poisson ratio.

The optical measurement solution proposed [29] is based in the use of a single camera with a spatial position and orientation allowing visualization of a set of passive targets evenly distributed in different regions, both in the static region surrounding the specimen and in the dynamic region of the tested specimen surface. The weak perspective model or the orthographic model with uniform scaling was adopted [29] allowing to establish a functional relation of the three-dimensional point georeferenced (expressed in millimetres, for example) with the corresponding bi-dimensional position in the image (usually expressed in pixels).

A measurement referential, composed of reference targets, was placed in front of the observation region in the masonry specimen at the minimum distance from the specimen surface (without contact), thus minimizing the observation depth difference to the monitoring targets fixed and scattered in the observation region (in the inner region of the referential), as shown in Figure 15.

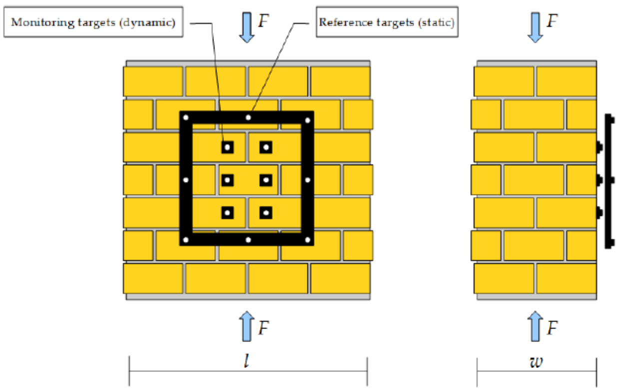

Figure 15. Schematic representation of the proposed optical measurement method.

Figure 16. Instrumentation of the masonry specimen.

The mentioned referential was subjected to dimensional measurement in an optical measuring machine, before the specimen testing, aiming at the determination of the three-dimensional georeferenced position of each reference target. The knowledge of these spatial coordinates supported the calculation of the scale coefficient in each acquired image, since the measurement referential is placed in a static region of the experimental setup (ensuring that it does not touch the specimen and it is not subjected to vibrations produced by the testing machine).

Solid and hollow ceramic brick masonry specimens were retrieved from the walls of one building built in the beginning of the 20th century in the city of Lisbon (Portugal), which was undergoing rehabilitation. The proposed optical approach was implemented by fixing monitoring targets in the specimen's ceramic bricks and placing the measurement referential with the reference targets close to the observation surfaces as shown in Figure 16 (displacement sensors are also visible, being used for validation purposes, without specimen collapse).

The recorded images were subjected to tailored digital image processing algorithm, in order to retrieve the image coordinates of both reference and monitoring targets, as shown in Figure 17.

The first stage of obtained results is related to the scale coefficient measurement samples (with a dimension equal to 28), from which an average value was obtained. Figure 18 illustrates the dispersion of scale coefficient values obtained for one of the used measurement referential.

Based on the specimen's length and width measurements, as well as the axial compression force readings obtained from the used universal testing machine, vertical and horizonal

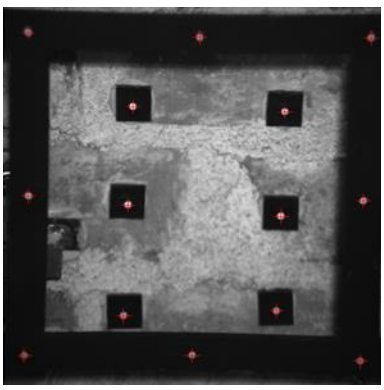

Figure 17. Example of targets image after digital processing, showing the determined centroids.

dimensional measurements were performed in the frontal and rear surfaces of the specimen, noticing the existence of both contact and optical measurement points not spatially coincident. From the collected data, stress vs. strain curves were obtained for the loading and unloading cycle corresponding to 1/3 of the fracture stress, as shown in Figure 19 and Figure 20.

Figure 20 shows the effect of noise in the strain measurements obtained by the optical dimensional measurements, when compared with the strain measurements obtained by the contact measurement chain (Figure 19). This is justified by the low spatial resolution of the acquired images, which affects the targets image coordinates which support the deformation measurement. A higher spatial resolution can be achieved with an image sensor composed by smaller pixels or by using a different lens that is capable of producing a higher image magnification with an acceptable narrow field-of-view.

These results were use in the determination of mechanical properties estimates and measurement uncertainties in tested masonry specimens. A detail discussion is shown in [29].

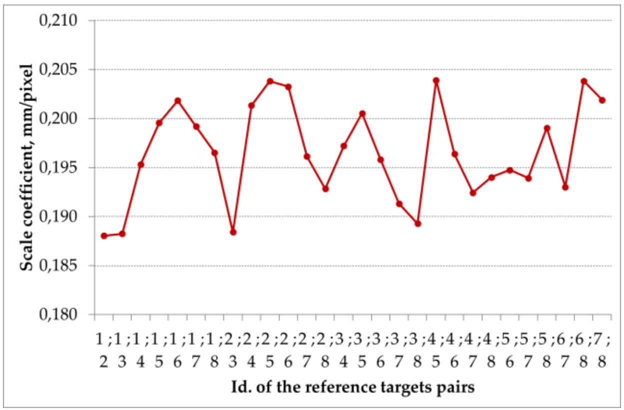

Figure 18. Dispersion of values related to the scale coefficient.

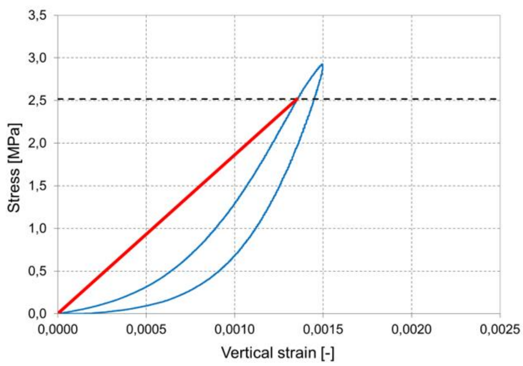

Figure 19. Stress vs. strain curve obtained by contact dimensional measurement.

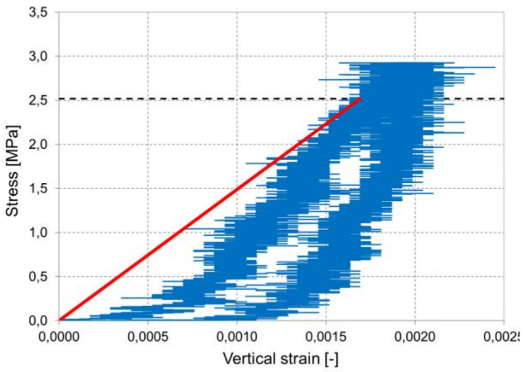

Figure 20. Stress vs. strain curve obtained by optical dimensional measurement.

7. CONCLUSIONS

This paper describes relevant contributions of Optical Metrology when applied in different testing and inspection activities in Civil Engineering, providing significant added-value in decision-making processes.

The wide diversity of testing and inspection activities in this context, together with the versatility of the measurement solutions and tools provided by Optical Metrology, motivates the development of new interdisciplinary R&DI work at LNEC, so far with promising results.

One of these fields is the development of Moiré techniques [30] applied in the digital modelling of reduced-scale hydraulic surfaces. Hydraulic experimental activities are frequently carried out in a dynamic regime; however, conventional invasive instrumentation is often unsuitable for real-time observations, making these experiments time-consuming and with reduced acquisition frequency. Moiré techniques have been successively applied in other scientific and technical areas, however, their application in the Civil Engineering context is still quite reduced.

Another research field being developed by LNEC in this context is the application of laser interferometry in the calibration of a strain measurement standard used for the geometrical evaluation of concrete testing machines (self-alignment and movement restriction) [31]. This measurement standard - a strain gauged column - is required to have a reduced instrumental measurement uncertainty (0.1 % or 5×10^{-6}), making laser interferometry an interesting suitable solution for this objective.

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REFERENCES

[1] G. Di Leo, C. Liguori, A. Paolillo, A. Pietrosanto, Machine vision systems for on line quality monitoring in industrial applications, Acta IMEKO 4 (2015) 1, pp. 121-127.
DOI: 10.21014/acta_imeko.v1i1.7

[2] G. D'Emilia, D. Di Gasbarro, E. Natale, Optical system for on-line monitoring of welding: a machine learning approach for optimal set up Giulio, Acta IMEKO 5 (2016) 4, pp. 4-11. DOI: 10.21014/acta_imeko.v5i4.420

[3] M. Lo Brutto, G. Dardanelli, Vision metrology and Structure from Motion for archaeological heritage 3D reconstruction: a Case Study of various Roman mosaics, Acta IMEKO 6 (2017) 3, pp. 35-44.
DOI: 10.21014/acta_imeko.v6i3.458

[4] VIM - International vocabulary of metrology - Basic and general concepts and associated terms, JCGM - Joint Committee for Guides in Metrology, 2008, pp. 16.

[5] M. Rosenberger, M. Schellhorn, G. Linß, New education strategy in quality measurement technique with image processing technologies - chances, applications and realisation, Acta IMEKO 2 (2013) 1, pp. 56-60.
DOI: 10.21014/acta_imeko.v2i1.92

[6] H. Schwenke, U. Neuschaefre-Rube, T. Pfeifer, H. Kunzmann, Optical methods for dimensional metrology in production, CIRP Annals - Manufacturing Technology 51, 2 (2002), pp. 685-699.

[7] L. Santos, Visual inspections as a tool to detect damage: current practices and new trends, Proceedings of Condition Assessment of Bridges: Past, Present and Future - A Complementary Approach, Lisbon, 2012.

[8] M. Pieraccini, G. Luzi, D. Mecatti, M. Fratini, L. Noferini, L. Carissimi, G. Franchioni, C. Atzeni, Remote sensing of building structural displacement using microwave interferometer with imaging capability, NDT& Int. 37 (2004), pp. 545-550, DOI: 10.1016/j.ndteint.2004.02.004

[9] K. Wong, K. Man, W. Chan, Monitoring Hong Kong's bridges. Real-time kinematics spans the gap, GPS World 12, 7 (2001), pp. 10-18.

[10] V. Khoo, Y. Thor, G. Ong, Monitoring of high-rise building using real-time differential GPS, Proceedings of the FIG Congress, Sidney, 2010.

[11] L. Martins, J. Rebordão, A. Ribeiro, Intrinsic parameterization of a computational optical system for long-distance displacement structural monitoring, Optical Engineering 54, 1 (2015), pp. 1-12, DOI: 10.1117/1.OE.54.1.014105

[12] L. Martins, J. Rebordão, A. Ribeiro, Thermal influence on long-distance optical measurement of suspension bridge displacement, Int. J. Thermophysics 35, 3-4 (2014), pp. 693-711, DOI: 10.1007/s10765-014-1607-3

[13] P. Henley, Sewer condition - classification and training course, WRC, 2017.

[14] L. Martins, M. Almeida, A. Ribeiro, Optical metrology applied in CCTV inspection in drain and sewer systems, Acta IMEKO 9 (2020) 1, pp. 18-24. DOI: 10.21014/acta_imeko.v9i1.744

[15] M. Rosenberger, C. Zhang, P. Votyakov, M. Peibler, R. Celestre, G. Notni, EMVA 1288 Camera characterisation and the influences of radiometric camera characteristics on geometric measurements, ACTA IMEKO 5 (2016) 4, pp. 81-87. DOI: 10.21014/acta_imeko.v5i4.356

[16] R. Hartley, A. Zisserman, Multiple View Geometry in Computer Vision, Cambridge University Press, New York, 2003.

[17] GUM - Guide to the expression of Uncertainty in Measurement, ISO - International Organization for Standardization, 1993.

[18] GUM-S1 - Evaluation of measurement data - Supplement 1 to the Guide to the expression of Uncertainty in Measurements - Propagation of distributions using a Monte Carlo method, JCGM - Joint Committee for Guides in Metrology, 2008.

[19] D. Brown, Close-range Camera Calibration, Proceedings of the Symposium on Close-range Photogrammetry, Illinois, 1971, pp. 855-866.

[20] R. Duarte, M. Rito-Corrêa, T. Vaz, A. Campos Costa, Shaking table testing of structures, Proceedings of the 10th World Conference on Earthquake Engineering, Rotterdam, 1994.

[21] A. Ribeiro, A. Campos Costa, P. Candeias, J. Alves e Sousa, L. Martins, A. Martins, A, Ferreira, Assessment of the metrological performance of seismic tables for a QMS recognition, Journal of Physics: Conference Series 772 (2016), pp. 1-16. DOI: 10.1088/1742-6596/772/1/012006

[22] Common Protocol for the Qualification of Research, Seismic Engineering Research Infrastructures for European Synergies, WP 3, NA 2.4, Deliv. 3, 2012.

[23] G. Lipinski, Mesures dimensionnelles par interférométrie laser, Techniques de l' Íngénieur - Measures et Contrôle, R 1 320, 1995.

[24] A. Caporale, F. Parisi, D. Asprone, R. Luciano, A. Prota, Micromechanical analysis of adobe masonry as two-component composite: Influence of bond and loading schemes, Compos. Struct. 112 (2014), pp. 254-263. DOI: 10.1016/j.compstruct.2014.02.020

[25] F. Greco, L. Leonetti, R. Luciano, P. Blasi, An adaptative multiscale strategy for the damage analysis of masonry modelled as a composite material, Compos. Struct. 153 (2016), pp. 972-988. DOI: 10.1016/j.compstruct.2016.06.066

[26] S. Kallioras, A. Correia, A. Marques, V. Bernardo, P. Candeias, F. Graziotti, LNEC-Build-3: An Incremental Shake-Table Test on a Dutch URM Detached House with Chimneys, Eucentre Research Report EUC203/2018U, Eucentre, 2018.

[27] A. Marques, J. Ferreira, P. Candeias, M. Veiga, Axial compression and bending tests on old masonry walls, Proceedings of the 3rd International Conference on Protection of Historical Constructions, Lisbon, 2017.

[28] EN 1052-1 - Methods of Test for Masonry - Part 1 - Determination of Compressive Strength, CEN - European Committee for Standardization, 1998.

[29] L. Martins, A. Marques, A. Ribeiro, P. Candeias, M. Veiga, J. Gomes Ferreira, Optical measurement of planar deformations in the destructive mechanical testing of masonry specimens, Applied Sciences 10, 371 (2020), pp.1-23. DOI: 10.3390/app10010371

[30] K. Gåsvik, Optical Metrology, 2nd edition, John Wiley & Sons, 1995, pp. 168-169.

[31] EN 12390-4 - Testing hardened concrete - Part 4: Compressive strength - Specifications for testing machines, CEN - European Committee for Standardization, 2019.