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Optical Metrology Applied to Testing and Inspection in Civil Engineering

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***Abstract* – Optical metrology has an increasing impact on observation and experimental activities in Civil Engineering, contributing to the investigation and development of innovative, non-invasive techniques applied in testing and inspection of infrastructures 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.

Keywords – Optical Metrology, Civil Engineering, Testing, Inspection.

I. 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. Assessment of the performance and behaviour of infrastructures, often involves monitoring and analysis under dynamic regimes. 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 of infrastructures. Moreover, the need for accurate measurements to support decision-making in critical processes 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) allowed 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 (Système International) 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 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. Moreover, the applications described emphasize the role of digital and optical systems, as the 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.

II. OVERVIEW OF OPTICAL METROLOGY

Optical Metrology is a specific scientific area of Metrology, defined as *the science of measurement and its applications* [1], 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, allowing assessing their limits and increasing their capabilities, in order to advance the knowledge of the studied phenomena.

In recent years, the technological development of computational tools has extended the Optical Metrology activity scope, by increasing measurement processes supported in digital processing of images obtained from optical systems. This activity is characterized by the detection and record abilities, without physical contact with the object and in a minor time interval, of a large amount of information (dimensional, geometrical, radiometric, photometric, color, 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. Within the dimensional Optical Metrology, a wide range of measurement applications is found, in a wide range of measurement intervals, from nanometer magnitudes up to the dimension of celestial bodies and space distances. In this context, measurement principles are usually grouped in three categories [2]:

(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;

(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.

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 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 geographic information systems, namely, through orthophotos and tridimensional 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) [3].

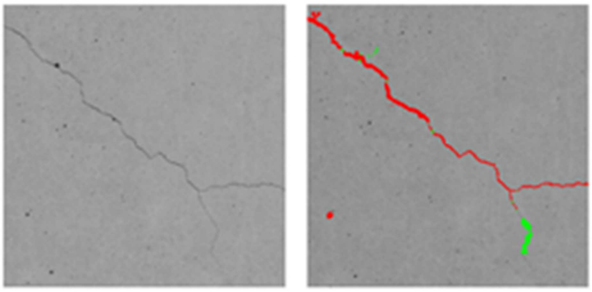

Fig. 1. Digital image processing of concrete wall surface image showing a crack

III. STRUCTURAL MONITORING OF A LONG-SPAN SUSPENSION BRIDGE

Optical Metrology has been successively applied by LNEC to a long-span suspension bridge observation context, allowing the development of non-contact measurement systems, capable of determining three-dimensional 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 and global navigation satellite systems can be compromised, 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 both the camera’s intrinsic parameters [4] 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.

This approach was implemented in the 25th of April long-span suspension bridge (P25A) in Lisbon (Portugal), for an observation distance near 500 m. In order 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).

Fig. 2. Active targets on the south tower foundation

Fig. 3. Digital camera installed in the stiffness girder

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 reduced the environment visible irradiance from many other elements in the observation scenario, thus improving contrast in the target image.

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. Figure 4 shows the vertical displacement of the bridge's main span central section corresponding to train circulation in the lower deck. In this figure, the peak detail of the steps related to the four carriage connections of the train is clearly noticed at about 120 s.

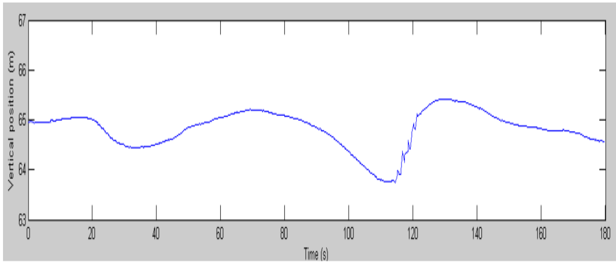

Fig. 4. P25A bridge central section vertical displacement during passengers train circulation

The results confirm the increase in the three-dimensional displacement magnitudes when the train circulates on the P25A bridge, namely in the vertical direction where a maximum (peak-to-peak) displacement of 1.69 m was recorded, with a 95% expanded uncertainty of 8.8 mm. This value is comparable to the vertical displacement measurements obtained in 1999, during a static loading test, following the structural reinforcement of the bridge for train circulation. In this previous test, a maximum vertical displacement of 3.15 m (2.37 m downward plus 0.78 m 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 (overloaded train), thus originating lower vertical displacements.

IV. 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 about the metrological quality of dimensional measurements based on images from CCTV inspections in drain and sewer systems.

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 [5] stresses the need of proper metrological characterization of the optical system – the CCTV camera – used in drain or sewer inspections, and defines two possible measurement models to be applied in this context – the perspective camera model and the orthographic projection camera model.

Research efforts were directed towards the evaluation of the measurement uncertainty following the GUM framework [6-7]. 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 deformation of the image, thus affecting the accuracy of dimensional measurements. To assess the impact of distortion in the image coordinate measurement accuracy, a Monte Carlo method [7] was used, given the complex and non-linear lens distortion model [5]. Figure 5 shows the estimates of the image variation due to the combined effect of radial and tangential distortions and Figure 6 presents the corresponding 95 % measurement uncertainty.

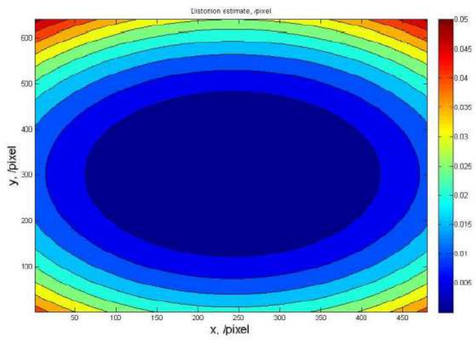

Fig. 5. Image distortion estimates in pixels

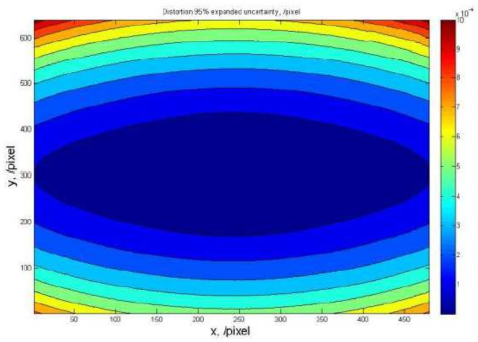

Fig. 6. Image distortion 95 % expanded uncertainties in pixels

The results from this study allowed a deeper discussion on the measurement accuracy in this field of inspection, namely, for the dimensional measurements obtained indirectly from the recorded inspection images. Measurement uncertainty analysis tools were developed and are now available to be used within the proposed approaches [5] and for the type of experimental input information, regarding estimates and related measurement uncertainties. These calculation tools also allow quantification of accuracy operational improvements, namely, due to changes in the field lighting, image analysis, CCTV camera selection and metrological characterization.

V. 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 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. 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.

Laser interferometry was used in this context to assess the linear displacement measurement accuracy related to each of the hydraulic actuators, due to the possibility of performing remote and non-invasive measurements with a high accuracy level in a harsh environment. In addition, the rotation of the testing platform was also measured to evaluate the effectiveness of the torsion bars action in the rotation restriction. These elements allow determining if the movement applied is physically representative of the intended seismic action.

Figures 7 and 8 show the geometrical configuration of the interferometric setup defined in the shaking table, respectively, for the calibration of the linear displacement measurement chain of a hydraulic actuator, and for the rotation measurement of the testing platform [8].

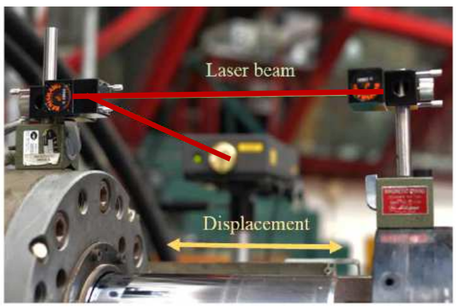

Fig. 7. Calibration of the linear displacement measurement chain related to a hydraulic actuator

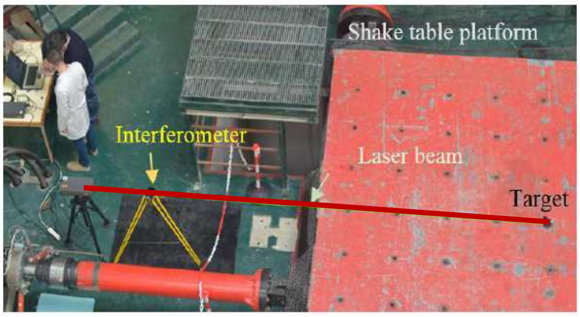

Fig. 8. Interferometric setup related to the rotation measurement of the testing platform

An example of the results obtained is shown in Figure 9, in terms of the calibration errors obtained for the linear displacement in one of the hydraulic actuators [8].

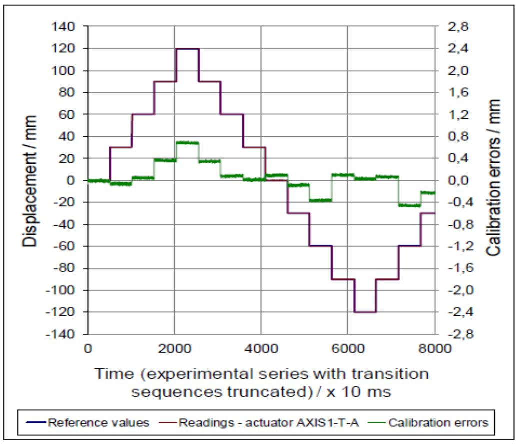

Fig. 9. Calibration errors of linear displacement

A more detailed description of this study and discussion of results can be found in [8].

VI. DESTRUCTIVE MECHANICAL TESTING OF MASONRY SPECIMENS

The application of Optical Metrology to the destructive mechanical testing of masonry specimens was motived by the possibility of obtaining non-contact dimensional measurements. In a destructive test, the use of conventional invasive instrumentation, such as 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.

Dimensional measurements allowed the calculation of strain in the tested specimens and characterizing their mechanical behaviour in terms of their elasticity modulus and Poisson ratio, which are key elements for the evaluation of seismic vulnerability and the effectiveness of structural reinforcement solutions.

The optical measurement solution proposed 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 (see [9] for the corresponding mathematical formulation), 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, 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 10.

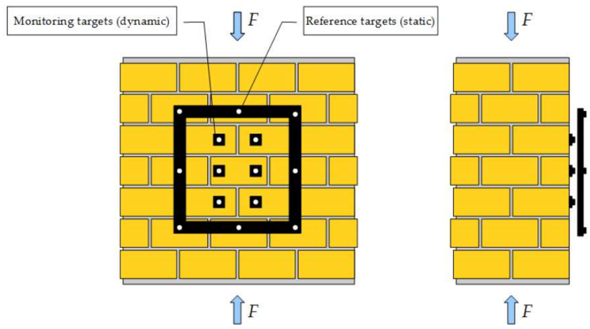

Fig. 10. Schematic representation of the applied optical solution

The mentioned referential was subjected to dimensional measurement, 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 is not subjected to vibrations produced by the testing machine).

Figure 11 shows the experimental implementation of this optical measurement solution, where displacement sensors are also visible (only for validation purposes, without specimen collapse).

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

Figure 12 shows an example of a stress versus strain curve, based on the dimensional measurements obtained with the optical measurement system developed. Detailed description of the obtained results can be found in [9].

Fig. 11. Instrumentation of a masonry specimen with reference and monitoring targets for optical measurement

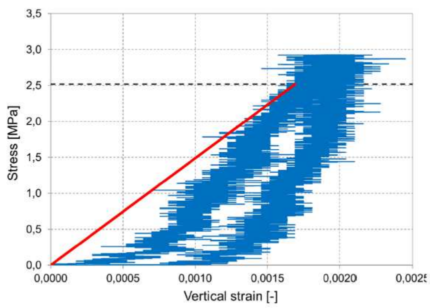

Fig. 12. Stress versus strain curve obtained in a masonry specimen mechanical test.

VII. FINAL REMARKS AND OUTLOOK

This paper describes significant contributions of Optical Metrology when applied in different testing and inspection activities in Civil Engineering, providing significant added-value in associated 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 research fields is the development of Moiré techniques [10] 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) [11]. This measurement standard – a strain gauged column – is required to have a reduced instrumental measurement uncertainty (0.1% or $5x10^{-6}$), making laser interferometry an interesting suitable solution for this objective.

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