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Conception and development of an optical methodology applied to long-distance measurement of suspension bridges dynamic displacement

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Abstract. This paper describes the conception and development of an optical system applied to suspension bridge structural monitoring, aiming real-time and long-distance measurement of dynamical three-dimensional displacement, namely, in the central section of the main span. The main innovative issues related to this optical approach are described and a comparison with other optical and non-optical measurement systems is performed. Moreover, a computational simulator tool developed for the optical system design and validation of the implemented image processing and calculation algorithms is also presented.

1. Introduction

In today's society, the mobility of persons and goods is assured by large transport networks where bridges are key elements with relevant impact on the social and economical development of a region or country. Therefore, it implies the need to assure the operational safety of bridges, usually by performing structural observation in order to characterize and analyse their performance in accordance with design safety requirements and behavior historical records, thus supporting maintenance and management decisions.

As in other relevant large structures, bridge observation is based on different field activities such as visual inspection and structural monitoring using measuring instruments placed on critical bridge structural elements. In general, different types of quantities can be measured, namely, temperature, wind velocity and direction, acceleration, rotation, extension and displacement.

In the studied case – long-span suspension bridge observation – the major concern relies in the measurement of three-dimensional displacement of the stiffness girder in the central section of the main span, being a challenge because conventional off-the-shelf instrumentation usually does not provide suitable solutions. A typical constrain, for instance, is found when using displacement transducers since it is not possible to define absolute reference points in the central section region. The use of other measurement methods such as geodesic observation and hydrostatic leveling are also considered inappropriate due to the dynamic structural behavior of the suspension bridge, usually characterized by having low frequency and high amplitude displacements, specially, in the vertical direction of its stiffness girder.

In recent years, research efforts have been seeking the development of non-contact and long-distance measurement systems able to provide adequate solutions for this problem. The three main approaches

proposed in this context are: (i) global navigation satellite systems (GNSS) [1]; (ii) microwave interferometry [2]; (iii) optical systems [3-6].
The first approach mentioned – GNSS – is supported on the use of antennas installed near the measurement region receiving signals from available satellites, thus providing absolute three-dimensional displacement measurements without any limitation regarding to the geographical location of the bridge. Although the absence of long-term instrumental drift makes this approach attractive, its accuracy is strongly dependent on several external factors, namely, the number and distribution of the on sight satellites, the atmospheric conditions and the multi-path effect resulting from multiple signal reflections on the bridge's metallic components (see Figure 1). This last effect also compromises the use of interferometric systems, since the emitted microwave signal can be multi-reflected on the metallic stiffness girder of a suspension bridge, thus affecting its measurement accuracy.

Figure 1 - The 25th of April suspension bridge in Lisbon (Portugal).

Optical systems composed of digital cameras and active targets, combined with the use of computer vision techniques, are not affected by the multi-path effect being considered among the most promising and adequate to give appropriate solutions for long-distance and non-invasive three-dimensional displacement measurement. In fact, they allow real-time and long-term monitoring, being able to measure low frequency and high amplitude dynamic displacements in suspension bridges, considering the absence of heavy rain or fog and (still to be assessed) low impact of refraction and turbulence effects.
This paper focus on the conception and development of an optical methodology applied to structural monitoring for three-dimensional dynamical displacement measurement in the central section of the suspension bridge main span. In comparison with other studied optical systems [3-6], the proposed methodology is considered innovative since it is supported on the use of a long focal length digital camera placed in the central section of the main span, oriented towards the tower foundation where a set of four active targets composed of near-infrared LEDs is located.
This optical configuration requires the previous intrinsic parameterization of the applied digital camera, being the experimental procedure a known difficulty when applied to long focal length lenses [7]. In addition, the accuracy of the measurements depends on several optical and mechanical influence quantities, namely, the stability of camera's intrinsic parameters and the mechanical connection to the bridge stiffness girder. This paper provides some solutions in order to support the aim that the variation observed for the camera position can be considered representative of the bridge's three-dimensional displacement in the installation section.
Since the optical measurement system is computationally complex, integrating digital image processing (which identifies and measures the target's position in sensor coordinates) combined with a triangulation operation by an iterative least squares procedure for the bridge's three-dimensional displacement determination, a validation procedure for algorithm implementation is required. For this purpose, a computer simulator was developed – to be described in this paper – allowing the user to generate digital images of active targets with known three-dimensional dynamic displacement of the applied digital camera. Consequently, the simulated target images can be used as input data for the

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computational algorithms, allowing a comparison between the output displacement values and the simulated camera displacement.

2. Measurement optical methodology

The conception and development of the optical system was intended to minimize the observation distance between cameras and targets and, being the main displacement measurement of interest located on the central section of the bridge's main span, this implies positioning cameras and targets on that particular region or near the tower foundations, thus reducing the impact of atmospheric phenomena and increasing the system's measurement sensitivity.

Following a photogrammetric approach, cameras placed on a tower foundation should observe not only the monitoring targets placed in the central section of the main span but also reference targets whose coordinates in a world referential are accurately known. However, the significant dynamic behavior of the suspension bridge structural elements implies placing reference targets on static regions, namely, in the tower foundation or anchorages opposite to the cameras. In large structures such as suspension bridges, this situation leads to observation distances ranging from 500 meters up to 1500 meters, implying the use of reduced focal length lenses that compromise the system's sensitivity and the use of unreasonable large targets, when employing simple and affordable off-the-shelf digital cameras.

The proposed optical methodology makes use of a digital camera with a long focal length lens (identical to the one presented in Figure 2) rigidly installed in the central section of the bridge's main span and oriented towards one of the tower's foundation where a set of four active reference targets is placed, being each target composed of several near-infrared LEDs organized in a circular geometrical pattern. This approach requires the accurate knowledge of the relative coordinates between the four targets (world referential) and it is supported on the previous intrinsic parameterization of the applied camera from which its focal length, principal point coordinates and lens distortion corrections [8] are accurately estimated.

Figure 2 – Off-the-shelf digital camera with long focal length lens.

This optical approach results in six unknown variables related to the camera's extrinsic parameters, namely, its position (three coordinates for the corresponding three-dimensional directions) and orientation (three rotation angles or the corresponding rotation quaternion), requiring the observation of, at least, four targets in order to obtain a stable solution in the triangulation process. The observed changes in the position of the camera are expected to be representative of dynamic displacement of the central section of the bridge's main span, if adequate solutions are implemented in response to the two main measurement concerns.

One specific concern is due to the transmission of high vibration frequencies which can compromise the displacement measurement accuracy, therefore, particular care must be given to the mechanical connection established between the camera and the stiffness girder, namely, through the use of vibration isolator materials. Another specific concern is related to the stability of the camera's intrinsic parameters, which must be regularly evaluated in order to evaluate internal damages caused by its continuous exposure to bridge vibration by traffic and wind actions.

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The intrinsic parameterization is a key issue of the proposed approach and it reveals to be a challenging task in the case of long focal length cameras while following the perspective or pinhole camera model. Three main parameterization approaches [7] are currently known: (i) the test-field method; (ii) the goniometric method; (iii) and the diffractive optical element (DOE) method. Since all of the mentioned parameterization methods are characterized by an identical accuracy level [7], the DOE method [10] is more attractive to implement due to a less complex experimental setup (stable laser source with accurate wavelength, beam collimator and DOE with known spatial frequency) when compared with the test-field method which requires a high number of targets distributed over a large structure and several observation stations placed far away from the targets (observation distances can be higher than 50 meters), and the goniometric method where an accurate goniometer must be used in order to determine the camera's orientation relative to a collimated light source. In addition, the DOE method is capable of providing stable and accurate estimates based on a single image of the produced diffraction spots on the camera's sensor while the other two methods require processing a high number of digital images.

In comparison with other studied optical measurement approaches, the developed system presents four main advantages: (i) higher sensitivity to the bridge's longitudinal displacement by using long focal length lens; (ii) the world referential is located in a static region where the relative spatial position and orientation of each target is previously characterized in a metrological laboratorial facility; (iii) the number of unknown variables is reduced to six in the triangulation process since the camera's position variation is considered representative of the bridge's three-dimensional displacement; (iv) only one camera is required to perform three-dimensional displacement measurement.

3. Computational simulator tool

The proposed optical methodology has a significant computational component which is a key element for the identification and the calculation of image coordinates of the observed reference targets. In addition to the previous knowledge of the camera's intrinsic parameters, the targets image coordinates are used in triangulation operation to determine its extrinsic parameters (position and orientation), from which the bridge displacement can be obtained.

Due to the complexity of the image processing and calculation operations, the detailed validation of the implemented algorithms is advisable. With this purpose, a computational simulator is used for generating digital image sequences of active targets obtained from a camera with known dynamical displacement. These images can be used as input data for the proposed digital image processing and triangulation algorithms. The obtained output displacement can be compared with the simulated displacement of the camera, as displayed on Figure 3.

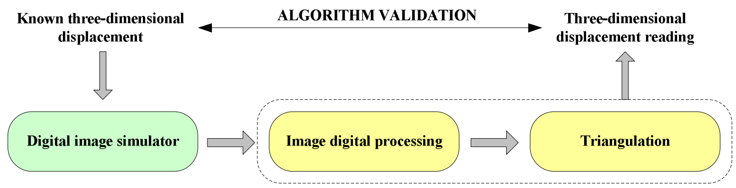

Figure 3 – Schematic representation of the algorithm validation process.

The simulator tool, build in a Matlab® environment, is capable of creating virtual observation scenarios from input variables which are grouped in four categories – camera, target, monitoring conditions and structural dynamics – as displayed in Table 1.

Table 1 – Categories of variables in the simulator tool.

Category	Variables
Camera	Camera type, number of cameras, spatial position and orientation
Target	LED type, number of targets, spatial position and orientation, type (static or dynamic target), shape (cross, rectangular or circular), number of LED lines, number of LEDs per line and LED spacing
Monitoring conditions	Initial and final monitoring instants, image acquisition frequency, turbulence, exposure time
Structural dynamics	Vibration mode, amplitude, frequency and phase

Pre-defined digital cameras and LEDs with specific dimensional, geometrical, radiometric or sensorial characteristics (mentioned in Table 2) can be selected in the simulator through the variables “Camera type” and “LED type”.

Table 2 – Subcategories of variables related to camera and LED types.

Subcategory	Variables
Camera type	Focal length, F-number, pixel dimensions, number of pixels, principal point coordinates, focal plane and sensor rotation angle, lens distortion parameters, optical transmittance, quantum efficiency, CCD sensor detection and saturation limits, reading and amplification noise, dark noise, dark signal non-uniformity (DSNU), photo response non-uniformity (PRNU) and quantization noise
LED type	Light intensity, wavelength and viewing angle

Based on the above input data, the simulator tool is able to provide realistic digital images sequences of the four reference targets (see Figure 4), as they were observed from a camera with known dynamic displacement.

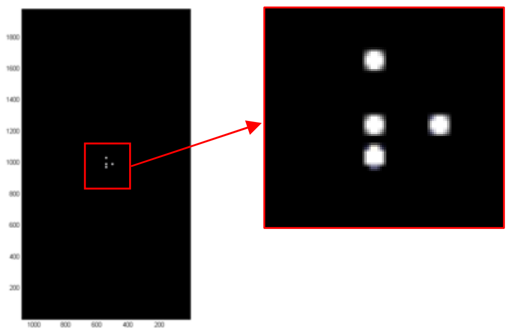

Figure 4 – Reference targets image (normal and amplified) obtained from the simulator tool.

Due to the high variability of observation scenarios (camera and targets position, orientation and mutual distance) and geometrical, radiometric and sensorial characteristics of the main optical components (camera and targets), this simulator tool is also useful in terms of measurement system design, namely, in the dynamical analysis of the camera’s field-of-view which, for the proposed optical approach, should always provide a complete image of the four reference targets.

4. Conclusions

This paper describes the main issues related to the conception and development of an optical methodology for long-distance measurement of suspension bridge dynamic three-dimensional displacement in the central section of its main span. By following an optical approach, this measurement method is not affected by the multi-path effect related to other emergent and complementary solutions such as GNSS and interferometric systems but it gathers their main advantages related continuous, real-time, non-contact and long-distance measurement [3-6].

When compared with previous developed optical systems for bridge observation, the described optical approach can be considered innovative in terms of the system's architecture and composition by placing only one digital camera in the central section of the bridge's main span, thus allowing the use of long focal length lens and consequently improving the displacement sensitivity and simplifying the triangulation procedures. In order to achieve an acceptable accuracy level, special attention must be given to the mechanical connection between the camera and the bridge's stiffness girder and to the long-term stability of the camera's intrinsic parameters.

The developed computational simulator tool has a relevant contribution for the validation of the algorithm implementation applied to digital image processing and the triangulation operations which gives the measurement estimates for the three-dimensional displacement. It is also a useful tool for the measurement system design taking into account the high variability of observation scenarios and optical system components.

Being a key issue for the success of the studied optical approach, work related to the DOE intrinsic parameterization of cameras composed of long focal length lens is already underway and results are expected to be obtained soon.

The proposed optical methodology is intended to have an important role in the suspension bridge safety monitoring context, by assuring the accurate measurement of dynamic displacement in its central section. In addition with other complementary measuring instruments and visual inspection activity, it will contribute for early structural failure detection, thus improving the bridge's safety.

The paper also illustrates the interdisciplinary character of the described study and its knowledge interaction with several scientific disciplines, namely, Civil Engineering, Optical Metrology, Photogrammetry and Computer Vision, and their individual contribution for solving this class of measurement problems.

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