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A 360-deg Digital Image Correlation system for materials testing

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ABSTRACT

The increasing research interest toward natural and advanced engineered materials demands new experimental protocols capable of retrieving highly dense sets of experimental data on the full-surface of samples under multiple loading conditions. Such information, in fact, would allow to capture the possible heterogeneity and anisotropy of the material by using up-to-date inverse characterization methods. Although the development of object-specific test protocols could represent the optimal choice to address this need, it is unquestionable that universal testing machines (UTM) remain the most widespread and versatile option to test materials and components in both academic and industrial contexts. A major limitation of performing standard material tests with UTM, however, consists in the scarce information obtainable with the commonly associated sensors since they provide only global (LVDTs, extensometers, 2D-video analyzers) or local (strain gages) measures of displacement and strain.

This paper presents a 3D Digital Image Correlation (DIC) system developed to perform highly accurate full-surface 360-deg measurements on either standard or custom-shaped samples under complex loading within universal testing machines. To this aim, a low cost and easy to setup video rig was specifically designed to overcome the practical limitations entailed with the integration of a multi-camera system within an already existing loading frame. In particular, the proposed system features a single SLR digital camera moved through multiple positions around the specimen by means of a large rotation stage. A proper calibration and data-processing procedure allows to automatically merge the experimental data obtained from the multiple views with an accuracy of 10^{-2} mm.

The results of a full benchmarking of the metrological performances of the system are here reported and discussed together with illustrative examples of full-360-deg shape and deformation measurements on a Grade X65 steel sample under tensile loading. The methodology demonstrated to be robust and accurate thus representing a viable practical solution to afford the modern challenges in the field of materials and components testing.

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1. Introduction

Recent advances in material science and material processing capabilities opened to new possibilities in building components and structures with superior mechanical performances due to a unique (for natural structures, [1]) or tailored (for engineered manufacts, [2–4]) distribution of mechanical properties. The inherent complexity of such structures, however, yields inevitably to increased difficulties in identifying and modeling their structural response and failure mechanics. This is partly due to the fact that, although advanced inverse characterization methods are capable to deal with complex geometries and mechanical behavior [5,6], there is still a scarcity of proper testing protocols able to provide the experimental data in the form required to feed the inverse procedure. In particular, to properly characterize the mechanical response of a material with location and orientation dependent properties (i.e. yielding to heterogeneous strain fields), it is mandatory to collect a highly dense set of shape and deformation data on the entire surface of the sample under multiple loading conditions.

Among the full-field optical techniques, Digital Image Correlation (DIC) [7,8] is particularly suited to be applied to material testing since it is robust, versatile and easy to use in both academic laboratories and industrial contexts. Briefly, stereo-DIC allows to obtain three-dimensional shape and deformation of a region of interest (ROI) on the surface of a sample provided with a natural or

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synthetic random pattern. The speckle pattern serves to match homologous points sets in the two angled views of the stereo-camera system by comparing the gray-level distributions over defined pixel subsets on the basis of a given correlation criterion [9,10]. Once homologous points are located in each image pair, stereo-photogrammetric principles [11] are used to track their 3D positions in space during the motion and/or deformation through a prescribed set of configurations. Experimental data obtainable with the DIC technique are characterized by high levels of accuracy and spatial and displacement resolutions which, however, strongly depend on camera/lens characteristics, pixel subset size and overlapping factor, speckle pattern quality, shape functions, stereo angle, etc. (see [12] for a more detailed discussion on the DIC metrological performances and [13] for an analysis on how DIC errors influence the identification results).

DIC full-field potentialities have been already exploited within standard material testing protocols with universal testing machines (UTM) to overcome the limitations of the associated sensors capable of providing only global (LVDTs, extensometers, 2D-video analyzers) or local (strain gages) measures of displacement and strain. DIC, in fact, has been used to retrieve the full-field deformation either on one-side (single camera) [14–16] and on two adjacent sides (two cameras) [17,18] of standard rectangular samples, as well as on given ROIs of generally shaped samples (two cameras) [19] during mechanical testing. However, although the information obtainable with standard 2D- and 3D-DIC systems allows to capture the eventual heterogeneity of the strain map over the investigated surface (e.g. the presence of shear bands, [15,17]), it is still not sufficient to inform a full 3D model of the sample/structure for a proper inverse characterization. A typical case of interest is represented, for example, by the measurement of the strain localization and necking that occur before failure in round specimens [20,21] under severe plastic deformation. The necking shape is commonly measured once the test is completed, whereas a continuous measurement of the necking evolution and strain localization would allow a better understanding and modeling of the failure mechanism and of the onset of the plastic instability. This is a particularly critical issue in the case of anisotropic materials, i.e. when the necking shape is not axisymmetric. In this case, advanced identification methods could be indeed applied [22] if experimental data over the full 360-deg surface of the sample were available.

A whole-body measurement is usually performed in one of the following ways: (i) the object is surrounded by a multi-camera arrangement [18,23–25], (ii) a single camera performs a full rotation around the object [26,27], (iii) the object is placed on a turntable and rotated with respect to a single fixed camera [28–30], (iv) the panoramic view of the object is obtained through object-specific catadioptric components [e.g. 31,32]. However, when a 360-deg measurement needs to be performed within a UTM, physical constraints (mainly related to the load frame configuration and to the geometry and size of the sample and gripping fixtures) restrict the applicability of the measurement modalities, leaving feasible only the implementation of the first two options listed above.

This work aimed to develop a DIC-based video system for performing 360-deg shape and deformation measurement into standard or custom UTMs given their widespread availability in both the academic and industrial contexts. Special attention was given to issues such as cost, ease of implementation and robustness of the calibration procedure with the purpose to encourage its prototyping and adoption also by users with limited technical experience.

The paper reports the rationale behind the choice of the final optical configuration, describes the experimental setup and the data analysis procedure, and presents the results of the benchmarking of the metrological performances of the measurement. Finally, the results of 360-deg measurements on a steel round specimen subjected to tensile load illustrate the capabilities of the system to obtain full surface heterogeneous displacement and strain maps with high levels of accuracy and resolution.

2. Materials and methods

2.1. System design

Prior to designing a 360-deg DIC-based video rig suitable to be used within a typical UTM during mechanical testing of materials and components, a list of specifications and constraints were identified as follows.

- The video rig should fit within the load frame usually consisting of two or four large supports/columns and should not interfere with the movement of the crosshead. Moreover, an easy mounting/dismounting of the rig should be guaranteed to better allow positioning and removing the sample and the fixtures.
- An unhindered view and constant and uniform illumination conditions should be obtained over the full surface of the sample throughout the entire duration of the test.
- The calibration procedure should be insensitive to camera mechanical instabilities due to vibrations and temperature fluctuations.
- A lean but robust data analysis procedure should rely on the sole image processing and be independent from other synchronized measurements (e.g. from LVDTs and encoders).
- The system should consist of a few and inexpensive off-the-shelf components assembled in order to allow a flexible adaptation to different sample sizes and geometries.
- The images should be captured over the full surface of the sample with an appropriate resolution to be useful for inverse characterization purposes. High magnifications (i.e. high spatial resolution and hence high DIC accuracy, see [13]) imply small field of views and, consequently, require the adoption of a large number of cameras/views to cover the full 360-deg panorama.

The latter requirement was crucial in the selection between the implementation of a single-camera or a multi-camera system. Notwithstanding multi-camera systems have been successfully used to perform 3D-DIC whole-body measurements, in fact, their application has been restricted to quasi-flat large objects viewed at long distances from a few (usually four) cameras [18,23,24]. The use of a multi-camera system would be impractical for small caliper quasi-cylindrical samples such e.g. the steel sample later tested in this study or such most of the biological samples commonly tested with UTM (tendons, ligaments, muscles, etc.) [33], due to the impossibility to place the required large number of cameras sufficiently close to the specimen. A viable solution would be the adoption of long distance microscopes with the limitation of increasing the already high investment cost related to the use and synchronization of a large number of cameras. For the reasons mentioned above, in this work we finally chose to adopt a 360-deg optical design featuring a single camera mounted on a slewing ring bearing that allows the sequential positioning of the camera around the specimen thus realizing a virtual multi-camera (VMC) system with no physical limitation on the number of views and on the angular step value (Fig. 1).

A prototype of the video-rig was setup on an optical bench, first to allow the development of the data processing procedure, and then to evaluate the metrological performances of the system under laboratory working conditions (Fig. 2). In a preliminary design optimization process, the performances of a scientific

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