Experimental Mechanics (2015) 55:1–8
DOI 10.1007/s11340-015-9991-6

Recent Advances and Perspectives in Digital Image Correlation

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Published online: 13 February 2015

As evidenced by the articles in this Special Issue, the advent of digital image correlation (DIC) and related methods for accurate, full-field deformation mappings has reverberated throughout the world of experimental mechanics and altered forever the way in which measurements are made and analyses are performed. No longer are investigators limited to average or point-wise measurements on general structures or smaller components. Instead, a new vista of opportunities in measurements and specimen design is opening. Though the paradigm shift may evolve slowly due to the prevalence of existing restrictive standards for certification-bound applications, there is abundant evidence indicating that the process is well underway and is gaining momentum. In the remainder of this Foreword, the editors initially provide a brief introduction to the special issue articles, providing a framework for the issues addressed by the authors and their relevance with regard to DIC methods. Then, the editors close out the Foreword by providing their thoughts regarding past, current and future developments that they envision in the next several years for DIC methods.

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Introduction to the Special Issue

The enclosed special issue includes articles spanning the entire range of digital image correlation methods including two-dimensional digital image correlation (2D-DIC); three-dimensional or stereo digital image correlation (3D-DIC or StereoDIC); volumetric digital image correlation (V-DIC) or digital volume correlation (DVC).

- Ten articles related to 2D-DIC
  - Error assessment related to camera resolution (1*)
  - Pin-reinforced composites (1)
  - Soft biomaterials (1)
  - Microscale imaging and analysis of metallic specimens under thermal and mechanical loading (2)
  - Earthquake measurements (1)
  - High speed imaging for dynamic loading of notched specimen (1)
  - Material property identification (3)
- Six articles related to 3D-DIC or StereoDIC
  - Profiling using two camera StereoDIC or single camera with diffraction grating (2)
  - Extrusion/particle flow studies (1)
  - High speed imaging for punch tests and/or pre-stressed woven glass epoxy specimens (2)
  - Confined concrete wall deformations (1)

* Denotes the number of articles in a particular category.

- Five articles related to volumetric imaging using V-DIC or DVC
  - Effect of sub-volume refinement
  - Increasing speed of throughput via improving iterative correlation process or through projection savings (2)
  - Applications including studies related to free-edge effects in composites or the internal deformation of a sugar-based material (2)

In the section 2D-DIC Articles, each of the 10 articles that utilizes two-dimensional digital image correlation are briefly summarized. Similarly, in the section entitled 3D-DIC or StereoDIC Articles, each of the articles using stereovision with digital image correlation are synopsized. In the section entitled V-DIC or DVC Articles, the articles that employed full volumetric "intensity" data to extract internal deformations are summarized. Once the brief summary of articles in the Special Issue is completed, then the authors highlight both the history and recent developments of modern DIC methods in the section entitled Past and Current Developments. They then give their personal look into the future, highlighting in the section entitled Outlook and Future Directions what they believe will be some of the aspects that will be experienced in the coming years. They close with an Acknowledgement to those who helped make this Foreword a reality.

2D-DIC Articles

Error Assessment and Spatial Resolution

The evaluation of measurement uncertainties is still an active area of research, both from a theoretical and practical point of view. For instance, Reu et al. studied the effect of the imaging system resolution on uncertainty levels when resorting to 2D-DIC and its relationship with speckle sizes. Fully resolved speckles and good contrast are two features that are important to lower the measurement uncertainty, and they may depend on lens resolution.

Pin-Reinforced Composites

Haldar et al. studied the size effect in pin-reinforced composites when subjected to uniaxial compression. 2D-DIC analyses have allowed the authors to understand the role of pins on the deformation mechanisms and to propose a scaling methodology for the compressive stiffness and Poisson's ratio based on the number of active pins per area.

Soft Biomaterials

Quantification of the mechanical properties of soft tissues enables understanding their normal physiological function, as well as the genesis, progression, and consequence of certain forms of disease. *Ex-vivo* mechanical testing of soft tissues is challenged by sample heterogeneity and anisotropy, the need to attain large sample strains for physiological relevance, and issues with sample mounting. One result of these challenges is the growing use of image-based techniques, especially digital image correlation methods, to measure local sample strain throughout a mechanical test. In the work of Shazly et al., the authors focus on particle/subset tracking within a sparse pattern to measure deformations on ring-shaped soft tissue specimens. Results from their studies show clearly that various factors must be considered for appropriate implementation of image-based local strain measurements in the context of soft tissue mechanical studies. These issues include the position of tracking markers/patterns on the sample surfaces and minimization of the effects of out-of-plane motion when using 2D-DIC for the measurements.

Microscale Imaging and Analysis of Metallic Specimens

One of the areas within the materials community where DIC has made a significant impact is in the study of microscale deformations in metallic materials. In the work of Pataky et al., the investigators tackled the difficult problem involving the use of DIC to analyze high temperature experiments. In their studies, the authors performed *ex situ* DIC measurements. This was made possible by resorting to a specialized speckle preparation (in the present case, air blasted alumina particles turned out to be a viable technique). The measurements have been performed at the grain level of a nickel-based superalloy. The 2D-DIC measurements clearly highlighted strain heterogeneities in the vicinity of various microstructural features (i.e., grain boundaries, triple points and slip lines).

In the work of Murasawa et al., the authors also conducted high temperature experiments while using DIC to measure both the microscale deformations that occur during inhomogeneous twin region nucleation and also the macroscopic strain fields that are present in a polycrystalline titanium metal subjected to uniaxial tensile loading. Using 2D-DIC measurements obtained during the experiment, the authors observed that, during the inhomogeneous twin region nucleation process, the distance between neighboring twin region nucleation points decreased with continuing deformation before the onset of rapid twin region size growth that produces avalanche nucleation behavior.

Earthquake Measurements

In the work of Rubino and Rosakis, the authors employed 2D-DIC in a laboratory earthquake setup capable of reproducing displacement and strain maps similar to those obtained in the field to gain understanding of the relevant fracture mechanics and to help interpret complex rupture features occurring in nature. By partially gluing two homalite plates together along an inclined surface and subjecting the plate to compressive load, dynamic rupture propagates along the inclined frictional interface. The authors employed 2D-DIC to characterize the full-field static displacement of the experimentally produced dynamic shear ruptures, showing the relative displacement (slip) along the frictional interface and other relevant response variables while noting that this is a first step towards using 2D-DIC to capture the highly transient phenomena involved in dynamic rupture.

High Speed Imaging

In the work of Xia, the author used a notched semi-circular bend (NSCB) specimen that has historically been employed to measure only the fracture initiation toughness in brittle materials. However, the author employed high speed cameras and 2D-DIC to measure more fracture parameters for the NSCB specimen as it undergoes dynamic loading in a Split Hopkinson Pressure Bar (SHPB) system. Using the transient displacement and strain fields measured by 2D-DIC during the fracture propagation process, both the fracture initiation toughness and the fracture propagation toughness were obtained successfully, demonstrating that DIC methods combined with high speed imaging allow investigators to extract more relevant quantitative information than has traditionally been obtainable with standardized experiments.

Material Property Identification

*T*he DIC method has impacted significantly the field of parameter identification. In this Special Issue there are three articles related to the integration of 2D-DIC measurements with simulations. Mathieu et al. developed the framework to combine 2D-DIC measurements with a weighted finite element updating method (FEMU) to estimate the elastoplastic constitutive parameters. The authors then applied the method to extract the elastoplastic parameters from data obtained during tensile loading of a commercially pure titanium dog-bone specimen. Performing both a two-step procedure and an integrated procedure (I-DIC), the authors have shown both I-DIC and FEMU methods provide similar results, with static (load) information required to obtain optimal identification of the parameters.

In the article of Passieux et al., the authors focused on the use of Finite-Element-based DIC methods for two-dimensional applications. Specifically, the authors considered the issue of the number of locations within an element where measurement data are needed to ensure accuracy in the FE-DIC solution. To address the required compromise between spatial resolution and measurement uncertainty, the authors opted to include measurement data at two different magnifications, with the high magnification images used to increase the number of measurements in a region for a given measurement mesh. Designated as a "multi-scale approach", the authors used optics-based theoretical developments in an effort to most accurately combine the two sets of measurements. After combining the measurement aspects with a multi-scale FEMU identification technique, the authors performed both simulations and nominally two-dimensional uniaxial experiments to show the effectiveness of the approach.

Fedele and his co-authors combined full-field, 2D-DIC measurement at the microscale with a modified simulation process to extract optimal estimates for interface properties (e.g. cohesive parameters). Specifically, the authors included both the boundary displacements along a prescribed boundary and the material parameters of interest in the identification problem. Using the FEM approach to discretize the region, issues such as ill-posedness and high dimensionality of the extended inverse formulation, exceeding a few thousand unknowns, resulted in the requirement for a new minimization strategy with regularization to overcome the issues and obtain reasonable estimates for both boundary conditions and interface parameters.

3D-DIC or StereoDIC Articles

Profiling or Shape Measurement

Though the development and validation of StereoDIC for solid mechanics studies was performed in the early 1990s, there continues to be interest in modifying various aspects of the method. In the article by Xia et al., the authors briefly describe their modified imaging process, where a test specimen is viewed through a transmission diffraction grating. Using this approach, multiple diffracted views of the same specimen are obtained and can be recorded. In this work, the authors extend the original DAIC method to permit quantitative measurement of 3D surface profiles by employing the well-known pinhole projection. The authors then perform two-dimensional digital image correlation (2D-DIC) analysis between the negative and positive first-order diffracted views and combine their results with pinhole projection to obtain the surface profile. Test results on well-defined cylindrical, conical and step surfaces are presented to illustrate the implementation and performance of the proposed surface profiling method.

The work of Orteu et al. is an example where the authors push the envelope to extract shape data with high accuracy near edges or shape changes. To achieve this goal, the authors outline a multi-step DIC algorithm that they developed to more accurately perform profiling of an object while preserving the accuracy near edges. It is worth noting that their algorithm, which includes a "bi-plane" condition for edges and a modified correlation criterion, works quite well using only a single pair of stereo images.

Extrusion/Particle Flow Studies

Stereo-based particle tracking is implemented by Zhao et al. to analyze the surface shape and motion of a submerged structure. The effect of multiple refractions has to be accounted for and the authors show how a stereovision system can be calibrated under such circumstances. Baseline experiments validate the proposed strategy, and the measurement of flow fields associated with the friction extrusion process in a lab model experiment illustrates the gain to be expected when compared to numerical simulations.

High Speed Imaging

Seidt and Gilat introduced a potential dynamic punch test specimen that takes advantage of StereoDIC to measure the deformation of the rear surface of a disk specimen subjected to dynamic punch-type loading. By comparing dynamic and quasi-static test results using the same fixtures, the authors clearly show that the punch geometry greatly influences the punching force and the failure mode. By using the StereoDIC measurements with appropriate simulation models, the authors conclude that the 3D surface deformation measurements provide essential data that can be used to construct and validate deformation and failure models.

In the work of Mallon et al., the authors use a shock tube to dynamically load a pre-tensioned, six-layer, orthogonally woven glass epoxy composite that has a small, central edge crack. Using a high speed StereoDIC system to monitor the deformations throughout the crack tip region for different primary fiber angles relative to the applied tensile loading as the crack propagated, the authors extracted the Mode I and Mode II stress intensity factors using an orthotropic theoretical model with the measured full-field displacements. As with the previous study, the StereoDIC measurements were essential to the extraction of the stress intensity factors.

Confined Concrete Walls/Large Structures

With the advent of 3D-DIC or StereoDIC, large scale experiments are now analyzed in academia and in industry as well. Specific challenges have to be met, among them calibration of the StereoDIC system and preparation of the specimen surface to obtain a high quality speckle pattern with the appropriate speckle size and intensity contrast. In this regard, Ghorbani et al. have studied mechanical tests on confined masonry walls via DIC analysis of stereo images. The random texture has been created by smoothing the rough concrete block surface using a white paste filler and then lightly bonding a polymer stencil so that black paint can be sprayed to obtain a well-defined random, high contrast, pattern on the surface. The authors were able to study the damage mechanisms by analyzing maximum principal strain fields. Crack opening displacement across several of the visible cracks were also assessed thanks to the measured displacement fields.

V-DIC or DVC Articles

Sub-Volume Refinement

Gates et al. proposed a refinement strategy to capture high levels of strain gradients but still control the displacement uncertainty level in regions with smaller gradients in local DVC. In the former part, fine sub-volumes are considered while larger ones are still suited in the latter case. The feasibility was shown for both an artificial pattern and also for an experimental case of a glass bead embedded in a PDMS matrix.

Novel Developments

It is well known that one of the key issues in DVC is the sheer size of data sets. To speed-up the calculations, Bar-Kochba et al. propose fast iterative procedures by adapting the image-deformation method used in particle image velocimetry (PIV) to DVC measurements. This type of approach can be accelerated by resorting to graphic processing units (GPUs), with their results indicating that local (i.e., sub-volume based) approaches can be made tractable on standard PC platforms.

In the work of Roux et al., the authors focused on ways to improve the speed of tomographic acquisitions to conduct DVC analyses. The authors introduced the concept of using a single ‘reference’ (i.e., fully reconstructed) volume with very few radiographs of the deformed configuration to estimate the volumetric displacement fields. Using their projection-based approach (or P-DVC), the authors proposed a GPU implementation and demonstrated that they can reduce the required projections to a very sparse set by performing DVC analyses on an experimental data set.

Volumetric Imaging Applications

An interesting application where DVC provides essential insight is illustrated in the work of Liu et al. In this work, the authors measured the response of sugar grains embedded in a binder. Using an incremental DVC approach, the authors correlated the measured internal deformations to the evolution of the microstructure, including debonding of the grains and void formation. Of particular interest in the DVC measurements was (a) the extraction of the representative volume element (RVE) for this material, which was found to be 10 times the average sugar grain size based on both the deformation measurements and observation of the grain structure and (b) the observation that debonding was the primary failure mode, occurring initially near the center of the cylindrical specimen, with no apparent grain fracture throughout the entire loading process.

In their studies, Lecomte-Grosbras et al. combined both DVC measurements on the interior of the specimen but near the edge and 2D-DIC measurements on the edge to investigate the well-known "edge effect" in composite laminates. After demonstrating that the DVC measurements were nominally consistent with the 2D surface measurements, the DVC data obtained after unloading was used to show that the residual displacement fields are nearly constant in each ply, with a well-defined displacement discontinuity at inter-laminar interfaces due to the accumulation of irreversible damage. Thus, the development and application of the DVC method provides heretofore unobtainable data regarding the interior deformations occurring within complex material systems.

Past and Current Developments

Since the initial development of digital image correlation methods over four decades ago, many challenges have been met and numerous applications have been. The first results were obtained by resorting to what is nowadays referred to as 2D-DIC (i.e., digital image correlation carried out on pictures acquired with a single camera, which gives access to in-plane displacement fields). The next developments, mostly during the nineties, required the use of two cameras. The method was designated 3D-DIC due to the method's ability to measure full-field 3D surface shapes and 3D surface displacements. They were spurred by national labs and industries willing to use such new techniques to analyze the behavior of complex structures for which 2D-DIC was not suitable. Stereo-vision algorithms were implemented and calibration procedures had to be introduced. Nowadays, 3D-DIC oftentimes is referred to as StereoDIC (instead of 3D-DIC due to the emergence and rapid expansion in use of DIC for fully volumetric measurements). With the ever-growing use of volumetric imaging in the biomedical field (e.g., CAT-scans, MRIs), mechanical tests were performed *in-situ* and the need for kinematic quantification soon emerged. *Digital Volume Correlation* (*DVC*), also known as *Volumetric-DIC*, appeared at the turn of the century. Over the years, the range of analyzed materials grew until virtually the entire spectrum encountered in material and mechanical sciences have been interrogated using DVC methods.

The first decade of the 21st century also saw the emergence of alternative approaches for which registration is no longer performed over small sub-images but over the whole region of interest. Commonly known as *Global DIC* methods, one of the reasons investigators opted to link full-field measurements with numerical simulations was to make the comparisons easier, possibly seamless, for identification and validation purposes. These procedures can be integrated in a single step to identify various mechanical parameters and are now being used with finite element codes when dealing with complex models in which the generalized degrees of freedom are the material parameters.

To reach the current state-of-the-art in 2D-DIC, many issues had to be solved. In contrast with PIV, which is the sister technique to 2D-DIC in fluid mechanics, small changes in displacement must be mapped with extremely high accuracy in solid mechanics, requiring sub-pixel resolution in the sensor plane positions. To achieve such resolution requires highly accurate gray level interpolation, either on the pictures themselves or on the correlation product. Since interpolation procedures were to be used, their effects on measurement results were evaluated. Similarly, more systematic studies regarding the effects of acquisition noise have been completed. Another factor that required study was the type of shape function to be used when matching subsets. This is of particular importance in StereoDIC where there can be substantial differences between the left and right images due to the orientation of the two camera views. Of course, having a higher order shape function could also be useful for cases involving large strains. In particular, previous research has shown that four basic attributes should be met by the pattern in each subset to ensure that the correlation process has a unique result:

(1) Isotropic pattern (no preferred orientation of pattern)
(2) Uniform pattern (same character of pattern throughout subset or element)
(3) Subset or element size much larger than order of shape function
(4) Shape function capable of accurately representing local deformations

With regard to the recording process, in the early years all images were obtained by analog cameras, requiring digitization hardware. Frankly, the process was error-prone due to slight, asynchronous shifts that occurred between lines in the images. These shifts introduced unwanted pixel motions in the recorded images that degraded the accuracy of the image-based measurements. Early digital cameras were certainly an improvement, though analysis of the images required that the digital data be subsequently transferred to a mainframe computer for storage and processing. As processing speed increased and storage costs decreased, mainframe computers were replaced by PCs, providing increased flexibility in the use of the DIC methods. Today's cameras have definition (pixel count) that exceeds 50 Mpixels for quasi-static studies. High speed cameras have reasonable definitions (0.5 Mpixel) at speeds exceeding 1 million frames per second, even more with specific ultra-high speed cameras using intensified CCDs, though the quality of the intensified images for image correlation may be reduced due to noise issues. In recent years, investigators have used both scanning electron microscopy and atomic force microscopy to perform quantitative analyses at reduced length scales. It is worth noting that the physical size of each pixel is less than one micrometer for the former, and can reach nanometric scales for the latter! On the other end of the scale, more and more applications now deal with meter to kilometer sizes when analyzing structures or even satellite pictures.

The sheer breadth of areas in which DIC methods are being used effectively today is hard to comprehend. Areas include stereoDIC for deformation measurements on submerged specimens; measurements during bulge experiments using both subset-based and global approaches; analyzing images obtained via infrared thermography to measure both displacement and temperature fields. To employ DIC methods in these areas, various artifacts associated with the image formation had to be accounted for during the analysis process to optimize the quality of the measurements.

As a final note on the evolution of 2D and StereoDIC methods, until the turn of the century, the number of images used to monitor an experiment was usually limited to a very few; tens of images at the most and generally one or two was all that was available! With the appearance and developments of digital cameras, this number increased into the hundreds in the previous decade. Nowadays, an experiment will typically yield a few thousands images per camera. Clearly, the increase in useful information has improved the understanding of physical phenomena. However, such large amounts of information require algorithms that can efficiently and accurately analyze images to improve throughput. This is an ongoing task that will benefit from any hardware improvements. As an example, the development and progress of fast GPUs for the gaming industries are also appealing to DIC developers as they implement algorithms to speed up the calculations.

In addition to 2D DIC and StereoDIC, true three-dimensional or *volumetric* imaging is a revolution in the making in a broad range of fields including biomechanics, fracture mechanics and material science. What was essentially hidden to the bare eye is starting to be revealed. By performing *ex-situ* or *in-situ* mechanical tests, it is now possible to monitor the material deformations in the bulk in a non-destructive way, thanks to DVC analyses. These studies are still mostly performed by resorting to in-house DVC codes, even as commercial versions have started appearing in very recent years. In parallel, *Global DVC* approaches are also being developed.

One of the limitations associated with volumetric imaging comes from the enormous amount of information that is gathered and contained in an image. This challenge is first met at the acquisition stage, where a complete tomographic scan may require up to one hour or more in some cases. Due to the long scan times, creep or other time-dependent phenomena may be responsible for significant motion between the first and last radiograph. This bias may degrade the resulting image and make it difficult (or impossible) to perform a proper reconstruction. Second, at the reconstruction stage, the cost of data processing promotes fast reconstruction techniques (such as the celebrated Filtered Back-Projection algorithm rather than algebraic variants that are more reliable but more demanding in terms of computation time). In addition to the scan time and reconstruction issues, the DVC process involves a large amount of data and data manipulation. Thus, efficient data processing becomes essential. GPU implementations can also constitute a solution, which has received some attention in the recent years. However, other strategies can be considered that could allow for a very significant reduction in the number of radiographs. It is worth noting that such an option generally involves more pronounced artifacts and thus some form of regularization may be required.

Even though 2D-DIC, StereoDIC, and to a lesser extent DVC, have reached a level of maturity that has led to commercial solutions, there are still many challenges to be met. It is worth noting that, in a number of developments underway, the final goal of the DIC analyses is gradually evolving from simply performing the raw measurements (i.e., displacement fields) to the end use of the measurements. This means that DIC codes will be driven by the expected output (e.g., shape metrology, identification of material parameters, control of mechanical parameters in a test), keeping in mind that the acquired pictures have noise embedded in them. To reach this new level, the output should be accompanied by robust error estimators to have sufficient confidence in the results. This new trend means that DIC is becoming one of the tools of choice for bridging the gap between experiments and simulations. The next section aims at discussing new directions that can be envisioned from the current state of the art and the previous remarks.

Outlook and Future Directions

The correlation methods, namely, 2D-DIC, StereoDIC and DVC, are image processing techniques. Consequently, any series of images with sufficient contrast have the potential to be analyzed. Consistent with this statement, any new imaging device is a potential candidate to acquire pictures that may be analyzed using DIC. Since the only data analyzed by a DIC method is contained in the images, then the process of image formation within the device, and all sources of bias and random errors that occur during imaging, have to be understood, quantified and then removed. If done correctly, the DIC method can provide trustworthy results with sufficient accuracy for the application of interest. The fact that SEM or even AFM pictures could be handled successfully proves that large spatial distortions that are dominant at low magnification and time-varying drift distortions that are dominant at higher magnifications have been successfully quantified and removed is an indication that even complex imaging artifacts can be understood. Consequently affordable equipment (i.e., low cost cameras and optics) can be utilized when appropriate image corrections are implemented in DIC codes, making them artifact-immune.

Similarly, new challenges arise from the use of tomographic and laminographic imaging. Here, artifacts embedded in the images during either acquisition or reconstruction may introduce bias in the measured displacement field. For example, when using lab tomography, a minute displacement of the X-ray source gives rise to magnification changes of the image, and hence to an apparent dilation that should not be confused with mechanical strains. Thus, the presence of reconstruction artifacts (such as rings) can degrade the accuracy of the measurements due to reductions or loss of contrast, especially when the natural microstructure of the material already has limited image contrast. It is therefore very important to address these issues so that DVC will be useful for a broader class of materials. Apart from progress in the reconstruction technique itself, one way to address the problem consists of numerically filtering images prior to a DVC analysis (e.g., ring artifacts can be significantly reduced). In this regard, it is noted that such filtering may alter the volumetric image such that some features in the "true" microstructure are lost during the reconstruction. All these developments will be especially useful once volumetric imaging systems combined with *in-situ* testing machines become "standard" in laboratories. Once this happens, DVC analyses could reach the resolution of 2D-DIC procedures so that the revolution observed in materials science will spread to the experimental mechanics community.

Need for Standards

Currently, no standards exist to assess the metrological performances of DIC, StereoDIC and DVC procedures. Clearly, it is desirable that such procedures emerge so that DIC measurements become acceptable to, say, certification agencies. Even without existing standards, as noted in the previous paragraph the ability to identify and minimize various image distortions is essential to obtain accurate DIC measurements. Once correction procedures have been implemented, it is then necessary to evaluate the metrological performances of DIC systems. To do so in the current environment, baseline studies are needed to ascertain just how accurate and stable the measurement systems are for a given configuration. Clearly, the more the user is aware of all the afore-mentioned issues, the safer s/he will be when studying the baseline results. This remark calls for good experimental practices to be developed and implemented as often as possible.

Given the importance of baseline studies, it is essential to re-emphasize a key aspect of DIC; it relies on image contrast to obtain accurate measurements (i.e., solve the optical flow problem). Even though the technique is more robust than one would initially assume, the results are dependent on the quality of the texture, including isotropy and uniformity of the pattern as noted previously. This means that a "unique value" for, say, the standard resolution is only global information. Hence, each new experimental configuration calls for performance assessment. Thus, future standards will have to recognize the importance of contrast (and pattern in general) and deal with it explicitly. Further, being a full-field measurement technique, a single number characterizing its performance should be replaced with complete full-field features (e.g., the covariance matrix if random uncertainties are to be evaluated).

With regard to applying a high contrast pattern for DIC, it is noted that the random texture can usually be applied very easily by spraying black and white paint for a lab-scale structure. However, for larger structures, this is not always possible. Other routes may be followed (e.g., masks for large structures, individual dot/feature appliques). Similarly, for small scale experiments (e.g., using SEMs), other approaches can be followed including lithography, surface etching or chemical particle development and bonding. Combining different scales of observations with consistent patterns is an area of active development. When dealing with tomographic pictures, the first generic difficulty is that the actual microstructure of the material can hardly be modified in the bulk to enhance the contrast. Some attempts were made (e.g., by adding particles or revealing grain boundaries) but at the risk of altering the mechanical response of the investigated material. This is a major difference with 2D-DIC and StereoDIC, where a homogeneous or transparent material can always be "speckle patterned". In synchrotron facilities, the use of phase contrast may enhance the differences between material phases and make them visible on the reconstructed volumes. However, this technique cannot (yet) be used on lab scale tomographs with polychromatic X-ray sources. Robustness when dealing with such sparse contrast textures is a major challenge that may limit the recourse to DVC for "high contrast" materials. To deal with such very difficult cases, DVC (and DIC) analyses can be assisted by mechanical regularization.

Continuing Need for Education

The sub-image based DIC and StereoDIC algorithms have reached a stage of maturity such that different commercial systems have been available for almost 20 years. More and more industrial and academic labs tend to rely on these ready-to-use codes. This trend explains why DIC is becoming one of the tools of choice in the experimental mechanics community. As the methods have gained acceptance, new users in industry, universities and government laboratories still need to be educated to the various aspects associated with DIC, requiring continuous updating of the current state-of-the-art as new development occur. In academia, it is common practice to have undergraduate students start learning about these techniques as part of their studies. However, this is by no means generalized in university curricula. Thus, summer schools are still organized at the graduate and post-graduate levels, or at conferences (e.g., organized by SEM) to extend the learning process for DIC methods.

If DIC is to be used on a regular basis in various industries, it also means that the human-machine interfaces should become even friendlier and easier to use. The issue of visualizing large amounts of data will also have to be addressed since more and more complex 2D (in space), 3D (in space and time or space) and 4D (space and time) fields will have more and more degrees of freedom (e.g., a few millions of degrees of freedom have already been achieved in DVC analyses). Standardized picture formats that enable fast visualization with multi-scale features are also desirable to achieve such goals.

Future Trends

Today, DIC and its extensions are operational and reliable for an ever wider range of materials and applications. It is envisioned that it will still undergo changes in the years to come as the issues outlined above are addressed and effective solutions developed. Such developments are essential to realize the full benefit of various imaging techniques when analyzing *in-situ* mechanical tests to improve insight and obtain quantitative data regarding the mechanical behavior of various materials and structures. In this regard, *comparison tools with numerical simulations* can be implemented. Implementation will allow the measured displacement fields to be used, for instance, for identification purposes. Various identification methods have been developed over the years, some of them only suited to full-field inputs. However, they have not reached a state in which fully seamless procedures for 2D-DIC, StereoDIC and DVC analyses can be performed for identification and validation of constitutive laws and numerical models. For global approaches, which have emerged more recently and have a relatively straightforward link with numerical simulations, not many commercial codes are currently available, though this is likely to change as the technology continues to evolve.

Taken together, all these developments will induce a change of paradigm, namely, in the 20th century many experiments were designed such that the gauge zone was uniformly loaded. With the advent of full-field measurement techniques, this is no longer needed and kinematic heterogeneities due to the sample geometry and/or material microstructure can be captured very accurately. *New experiments can now be designed so that the sample geometry and loading history are optimized with respect to the sought material parameters. The next step along that direction is to consider driving the experiments with simulations.* For example, to validate constitutive models, realistic loading histories are desirable. Such loading histories can be obtained either by offline or online interactions between the experiment and the simulations. The simulations can be updated by extracting the actual boundary conditions of the monitored test, with the parameters in the constitutive model obtained during the simulation by appropriate matching of measurements and predictions. *Controlling experiments* via *simulations, and vice-versa, is now technically possible thanks to* (a) development of the DIC methods, (b) current and forthcoming increases in computer power, and (c) development of appropriate algorithms for implementation.

Moreover, *linking CAD tools, FE simulations and DIC procedures is becoming possible.* For instance, finite-element based DIC procedures were introduced ten years ago and have been used in various applications since then. More recently, StereoDIC approaches have been developed using the CAD description of the observed surface. Similarly, FE-based surfaces can also be analyzed. Consequently, from the design of an experiment to the validation of a new structure or assembly, all of the tools can be integrated into a toolbox for the modern experimentalist who also needs to utilize CAD and FE software. To avoid creating “Babel towers”, it will mean that the world of experiments and simulations should be integrated effectively so that “simulation-based engineering sciences” will emerge.

Lastly, it is noted that the DIC methods are only one of many tools that experimentalist may require to analyze experiments via full-field evaluations. For modern, muli-disciplinary applications, investigators often need to obtain measurements for multi-modal fields (e.g., displacements, textures, lattice strains, temperatures, electrical conductivity). *Thus, it is envisioned that several measurement methods will be combined and synchronized data acquired for all aspects of interest, providing an extremely broad set of measurements from a single experiment.* As a direct consequence, such experiments should allow the experimentalist to limit their number since the output from a single one will be far richer than what is currently achieved in academia and, just as importantly, in industry.

Acknowledgments The authors would like to warmly thank Prof. Jean-José Orteu, Dr. Stéphane Roux and Dr. Hubert Schreier for very fruitful discussions on the subjects covered in the present discussions.