3rd International Conference on Tomography of Materials and Structures
Lund, Sweden, 26-30 June 2017, ICTMS2017-58

# *Imaging material kinematics, models and mechanical properties*

Clément Jailin *1, Arturo Mendoza †1, Ante Buljac ‡1, Thibault Taillandier Thomas §1, Jan Neggers ¶1, Benjamin Smaniotto ‖1, Amine Bouterf **1, François Hild ††1, and Stéphane Roux ‡‡1

[1]LMT, (ENS Paris-Saclay/CNRS/Univ. Paris-Saclay), 61 Avenue du Président Wilson, 94235 Cachan, France

**Keywords:** x-ray tomography, in-situ mechanical testing, digital volume correlation

**Summary:** In situ mechanical testing in a tomograph may provide a series of 3D images all along a loading history, from which 3D kinematic fields, and finally mechanical properties can be measured. A crucial tool for achieving this goal is Digital Volume Correlation, DVC, numerous variants of which will be reviewed, as well as the new horizons they open.

## 1. INTRODUCTION

Tracking in time the evolution of a solid using tomography, or 4D imaging in short, yields an unprecedented wealth of information to reveal the mechanical behavior of materials. To access this characterization, a first step is to extract motions from these 4D images through "Digital Volume Correlation", DVC [1]. The latter exploits the property that the microstructure that is revealed via tomography is advected in time without alteration. 4D images are denoted as $f(\boldsymbol{x}, t)$ where $(\boldsymbol{x}, t)$ are the space and time coordinates of each considered voxel. The conservation of microstructure is expressed as

$$f(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x}, t), t) = f(\boldsymbol{x}, t_0) \tag{1}$$

where $\boldsymbol{u}$ is the Lagrangian displacement from the reference configuration considered at time $t_0$. DVC consists in solving the inverse problem of the determination of $\boldsymbol{u}$ from $f$. Since the pioneering work of Bay [2], DVC has flourished and has become a very powerful tool to address a large variety of problems where the kinematics may not be the central focus.

## 2. APPLICATIONS

**• Hybridization with mechanical modeling**

DVC is an ill-posed problem. Yet, ill-posedness can be circumvented by choosing an appropriate subspace, $\mathscr{F}$, in which $\boldsymbol{u}$ lives. In any given material or test, the more fitted $\mathscr{F}$, the better the conditioning of the problem and the smaller the uncertainty of the result. For instance, $\boldsymbol{u}$ can simply be constrained to be continuous by using finite-element type descriptions of the kinematics, which are supported by meshes [3]. In addition to using a mesh, a penalty can be imposed for fields not being *locally* the solution to an elastic problem, a regularization that is both numerically convenient and mechanically satisfactory [4].

When mechanical identification is targeted, a tighter bond with mechanical models can be designed by numerically generating a basis for $\mathscr{F}$, which correspond to sensitivities (variation of the displacement field) with respect to any unknown parameters, be they constitutive, or describing boundary conditions or shape. This approach is called *Integrated DVC* [5]. The limit to this strategy is the risk of model error where the

*e-mail: clement.jailin@ens-paris-saclay.fr
†e-mail: arturo.mendoza_quispe@ens-paris-saclay.fr
‡e-mail: ante.buljac@ens-paris-saclay.fr
§e-mail: thibault.taillandier-thomas@ens-paris-saclay.fr
¶e-mail: jan.neggers@ens-paris-saclay.fr
‖e-mail: benjamin.smaniotto@ens-paris-saclay.fr
**e-mail: amine.bouterf@ens-paris-saclay.fr
††e-mail: francois.hild@ens-paris-saclay.fr
‡‡e-mail: stephane.roux@ens-paris-saclay.fr

actual solution would not belong to $\mathscr{F}$. It is thus essential to evaluate the registration quality from the residual field, $\eta(\boldsymbol{x}) \equiv f(\boldsymbol{x}+\boldsymbol{u}(\boldsymbol{x},t),t) - f(\boldsymbol{x},t_0)$, that often points out to directions for model enrichment.

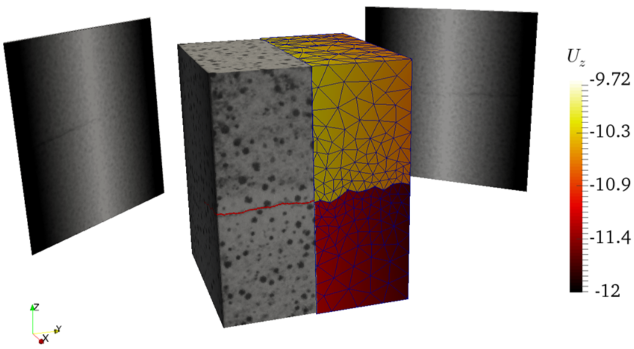
**• Topological difference and model matching**

DVC can also be used as a tool for comparing two different — though nominally similar — objects or industrial parts, with the idea of quantifying shape or microstructure differences. Consequently displacements are not physical motions, but the mathematical transformation to superimpose a specimen onto a "master", which is considered to be the reference. From the displacement fields, shape offsets or microstructure distortions (e.g. due to processing conditions) can be assessed. If not too stringent constraints are imposed on the displacement field, the residuals only contain differences that cannot be resolved from a chosen geometric transformation. The latter are henceforth called "topological differences", and constitute intrinsic signatures of processing defects.

One step further consists in registering an actual specimen with its virtual (and nominal) definition (e.g. its CAD model). This comparison calls for an extension of the above brightness conservation (e.g. gray levels have to be ascribed to different phases). Moreover, the typically modest texture and non-smoothness of the problem require a suited numerical treatment, which is possible without modifying the DVC core procedures. This application also opens the way to refine acquisition parameters and correct artifacts using the same approach.

**• Projection-based DVC**

When considering the temporal changes of a specimen, the microstructure usually does not change severely in time except for its motion. Hence, after a first reconstruction has been performed, the only remaining unknowns are the sample kinematics. The latter generally demands much less data than the number of voxels, and even more so if a mechanical model is involved. Hence performing successive reconstructions is both costly and unnecessary. It is therefore natural to try to read the kinematics directly in the radiographs, and to reduce their number (or rather increase the time resolution). This procedure, *Projection-based DVC* [6], as illustrated in Figure 1, was shown to be effective with several orders of magnitude gain in needed number of projections.




**(a)**

**Figure 1:** Crack opening in the sample shown in the center can be obtained from an initial tomography, two projections in the deformed state and an appropriate modeling schematized by the finite element mesh onto which the vertical component of the displacement field is color-coded

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