Unwrapping Textile Fabric

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Summary: Textile fabrics can be numerically re-arranged into their theoretical configuration using Digital Volume Correlation. Such configuration corresponds to the ideal weaving pattern, as can be defined by virtual means (FE, CAD). The procedure allows for woven composites volumes (as those obtained from tomography) to be unwrapped into a more convenient representation. A virtual scenario is used to validate the approach.

1. INTRODUCTION

Composite materials are fast becoming key in many applications mainly due to their very attractive specific properties (e.g. strength to weight ratio), especially those of woven composites. These are conformed by yarns (reinforcement phase) woven after a pattern and held together by a resin (matrix phase). Evidently the increasing interest in these materials has generated a high demand for proper characterization methods as well as for accurate simulations. In this context, X-ray computed tomography has opened new horizons.

As it would be expected for woven fabrics, it is thus important to identify and follow the weaving itself (i.e. the yarns) from a tomographic image. Clearly, manual intervention is possible for extracting such information. Needless to say, a tedious and time consuming operation which could suffer from operator bias and lack the required precision. Alternatively, advanced image processing methods are also available. However they often are too specialized or overly sensitive to slight changes on the input image (resolution, noise, artifacts) or to the material itself.

In order to provide a wider perspective, it is proposed to consider the material as in a so-called *deformed* or *wrapped* configuration with respect to a *reference* one. Here the reference configuration represents the theoretical arrangement of the textile, as obtained by the weaving pattern simply being tessellated (tiled). This form is usually easily accessible through virtual modeling of the element (FE, CAD).

As formulated, the problem is actually quite close to that encountered in Digital Volume Correlation (DVC): to retrieve the displacement field relating both configurations. Here a virtual scenario is presented as a way to probe a possible numerical strategy using DVC.

2. PROPOSED APPROACH

Digital Volume Correlation [1] is a widely used technique for measuring the internal displacement field between a pair of volumes (generally obtained from tomography), based on the brightness conservation assumption [2]:

$$f(\boldsymbol{x}) \approx g(\boldsymbol{x} + \boldsymbol{u}(\boldsymbol{x})) \equiv \tilde{g}(\boldsymbol{x}) \tag{1}$$

where $f(\boldsymbol{x})$ and $g(\boldsymbol{x})$ are the three-dimensional images corresponding to the reference and deformed configurations respectively, and $\boldsymbol{u}$ is the sought displacement vector field.

Given that the problem is ill-posed, a better conditioning can be obtained when the displacement field is restricted to a space of low dimensionality. A convenient choice is a set of kinematic fields, $\psi_i(\boldsymbol{x})$, such as those used in the framework of the finite element (FE) method:

$$\boldsymbol{u}(\boldsymbol{x}) \approx \sum a_i \psi_i(\boldsymbol{x}) \tag{2}$$

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Finally, the overall solution is given by the vector $\boldsymbol{a}$ that minimizes the squared norm of the residuals $\eta = f - \tilde{g}$ over the region of interest Ω. A classical iterative Newton-Raphson routine leads to the linear system

$$\boldsymbol{M}\Delta\boldsymbol{a} = \boldsymbol{b} \tag{3}$$

where

$$\boldsymbol{M}_{ij} = \int_{\Omega} (\Phi_i \cdot \Phi_j)\,\mathrm{d}\boldsymbol{x} \qquad \boldsymbol{b}_i = \int_{\Omega} (\Phi_i \cdot \eta)\,\mathrm{d}\boldsymbol{x} \qquad \Phi_i(\boldsymbol{x}) = \nabla f(\boldsymbol{x}) \cdot \psi_i(\boldsymbol{x}) \tag{4}$$

As such, the vector $\boldsymbol{a}$ containing all the unknown degrees of freedom is updated with $\boldsymbol{a}^{k+1} = \boldsymbol{a}^k + \Delta\boldsymbol{a}$, this allows to recompute $\tilde{g}$ and η. The procedure is repeated until convergence.

As can be seen from equation (4), DVC relies heavily on the image gradients provided by the texture of the studied material. However, the virtual scenario presented here has to deal with a very poor texture. Any image obtained from a virtual model will only contain non-zero gradients on the boundaries of the individual virtual structures. Thus a direct implementation of the DVC strategy will fail to converge.

Then, it is proposed a relaxation scheme that will broaden the gradients produced by the boundaries in order to progressively increase the correlation length. Naturally, the procedure hints to the use of a Laplacian pyramid. The pyramid levels are iteratively created through the use of a Gaussian filter with a blur radius of $1 \times 1 \times 1$ voxels, followed by a $2 \times 2 \times 2$ down-sampling operation. This coarse-to-fine approach allows for a smooth convergence since the found solution at a given level is used as a initialization for the lower one.

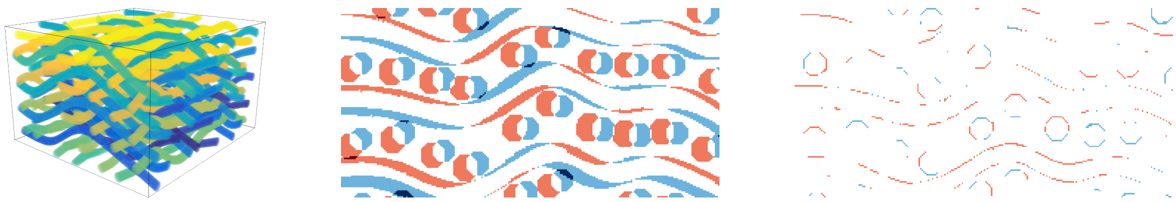
3. RESULTS

A pair of images obtained from a virtual model constitute the virtual scenario used to test the proposed approach. The virtual model consists of three-dimensional structures that represent the yarns. These are arranged in a *real* fashion since the topology was extracted from a tomographic image. Naturally, not only is it possible to label each one of the yarns but also to categorize them into one of the two orthogonal orientations. This results in three categories to be analyzed: resin, warp yarns and weft yarns. This is considered as the *reference* configuration.

Afterwards, the model is virtually deformed using any arbitrary displacement field in order to obtain the *deformed* configuration. The displacement field chosen for the task is one that has already been seen in this type of fabrics. Then the pair of images can be constructed from the reference and deformed virtual models by means of a discretization of the continuous three-dimensional space into *voxels* and by assigning the corresponding intensity value (category).

Due to the size of the images, four pyramid levels are used. The kinematic basis is defined for all levels of the pyramid using a $14 \times 16 \times 8$ structured regular mesh composed of only H8 (hexahedron) finite elements. The element size at the smallest scale is $2 \times 2 \times 2$ voxels, and uses the same scaling factor as in the pyramid.

Finally, an excellent agreement between the imposed and measured displacement field is observed, as it can be seen in the image of residuals. These results are encouraging, since they do perform extremely well in spite of a complex deformation, a poor texture, and a relatively poor chosen kinematics.



(a) **(b)** **(c)**

Figure 1: (a) Volumetric rendering of the virtual model in its reference configuration. Slices of the image of residuals before and after DVC are shown in (b) and (c) respectively.

References

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