On the high-fidelity digital twinning of image-based mechanical tests in an HPC environment

P. Bouda[1a]

[1]Université Paris-Saclay, CEA, Service d'Études Mécaniques et Thermiques, 91191 Gif-sur-Yvette, France

[a]pascal.bouda@cea.fr

Abstract. Assessing image-based tests ability to characterize materials remains a significant challenge, in particular when one is keen to take into account uncertainties. In particular, rendering high-fidelity images in the view of virtual testing may require a prohibitive computational cost. In this work, we illustrate how High-Performance Computing (HPC) paradigms can help to gain efficiency and open up the way to unprecedented accuracy levels.

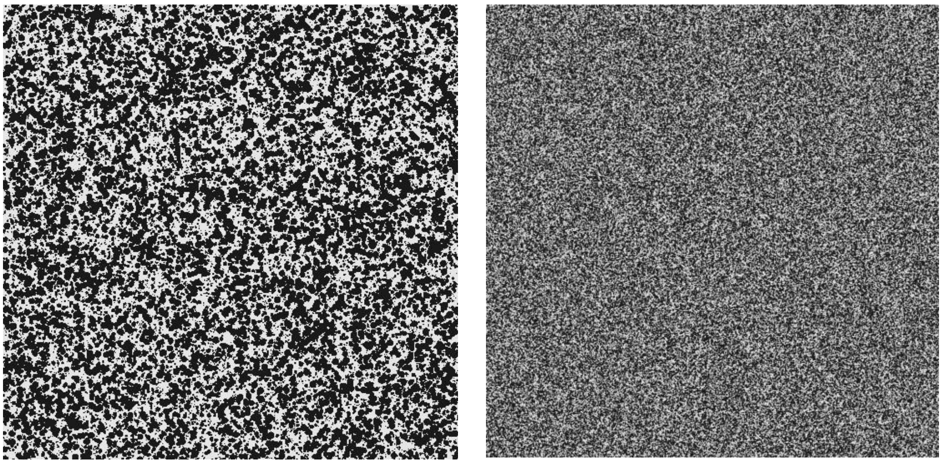
Introduction. Full-field measurements techniques are getting an exponential attention from the material testing community. Owing to the continuous development of camera sensors, it is now possible to image tests with a spatial resolution which can reach several millions of pixels. The combination of such optical techniques and the associated tests can be referred as Material Testing 2.0 [1] because it involves a shift in test monitoring, from pointwise to multidimensional kinematic fields extraction.

Uncertainty quantification is one of the major challenges in the adoption of such methods. In addition to be a requirement towards standardization, the latter might be considered while exploring the test design space to select test parameters. To determine uncertainties related to the metrological toolchain - from image acquisition to kinematic fields processing - one mainly relies on virtual images which mimic the digitization process through a camera, so that they are a critical asset while digital-twinning image-based tests.

State of the art. The literature often considers the virtual images concept in an "image deformation algorithm", where an initial pattern (grid, speckle) is distorted to follow a specimen deformation. In this case, the aim is to validate a numerical procedure to extract material constitutive parameters, or to optimize test parameters related to the specimen mechanical behaviour. Therefore, the effort was done on the way to render warped patterns using node displacements from a finite element mesh. While first attempts were suffering of a spatial accuracy loss due to spurious interpolations, algorithms were improved to avoid them [2]. However, considering the latter strategy involves an intensive use of several computational geometry concepts. Besides, several algorithms were also developed to render high-fidelity speckles. As first methods were including spurious interpolations, more recent ones were developed to cancel them for any deformation state [3]. However, such algorithms are very costly since a Monte-Carlo numerical integration is involved.

Developments and results. To avoid fidelity trade-offs and render images in a reasonable time, we propose a multilevel acceleration of all procedures, with a focus on aforementioned algorithms bottlenecks only. Indeed, most of the problem complexity comes from the very large number of points (e.g., the Monte-Carlo evaluation points) for which a digitization subroutine is called (possibly several billions per image). Therefore, we propose first to decompose that global rendering problem into smaller subproblems owing to a spatial domain decomposition, hence a lower local complexity for point location problem for instance. This technique is widely used in the high-performance computing community for multiphysics, because all subproblems can contribute (almost) independently to the parallel solving of a global problem. The corollary challenge is then to handle subdomains boundaries. Here, this means dealing with speckle dots and/or finite element mesh cells (in case of an image deformation procedure) that can belong to several domains. In this work, a Python generic module was developed to handle such situations, this enabling a fully parallel image rendering, even for the data I/O. Several improvements were also introduced within the algorithms themselves. For instance, both inverse mapping procedures necessary to either determine if an integration point is inside a black dot or not and the one to locate an integration point within a mesh were accelerated, owing to a custom hierarchic tree and a tailored grid search respectively.

The developed library was used to render speckles for different cases. After a verification of the rendered images (Fig. 1), both strong and weak scaling were achieved for an affordable number of CPU cores (Fig. 2). Indeed, a proportional speedup is observed when the number of processors grows for a fixed problem (strong), and a similar computation time is observed when both the number of processors and problem size grows (weak). These results validate our implementation choices, even if the domain decomposition might be irrelevant in an unusual but possible situation, which is a small number of pixels and/or number of integration points (see Fig. 1).



(a) (b)

Fig. 1: Example of rendered boolean speckles – (a) 500x500 pixels (b) 2000x2000 pixels

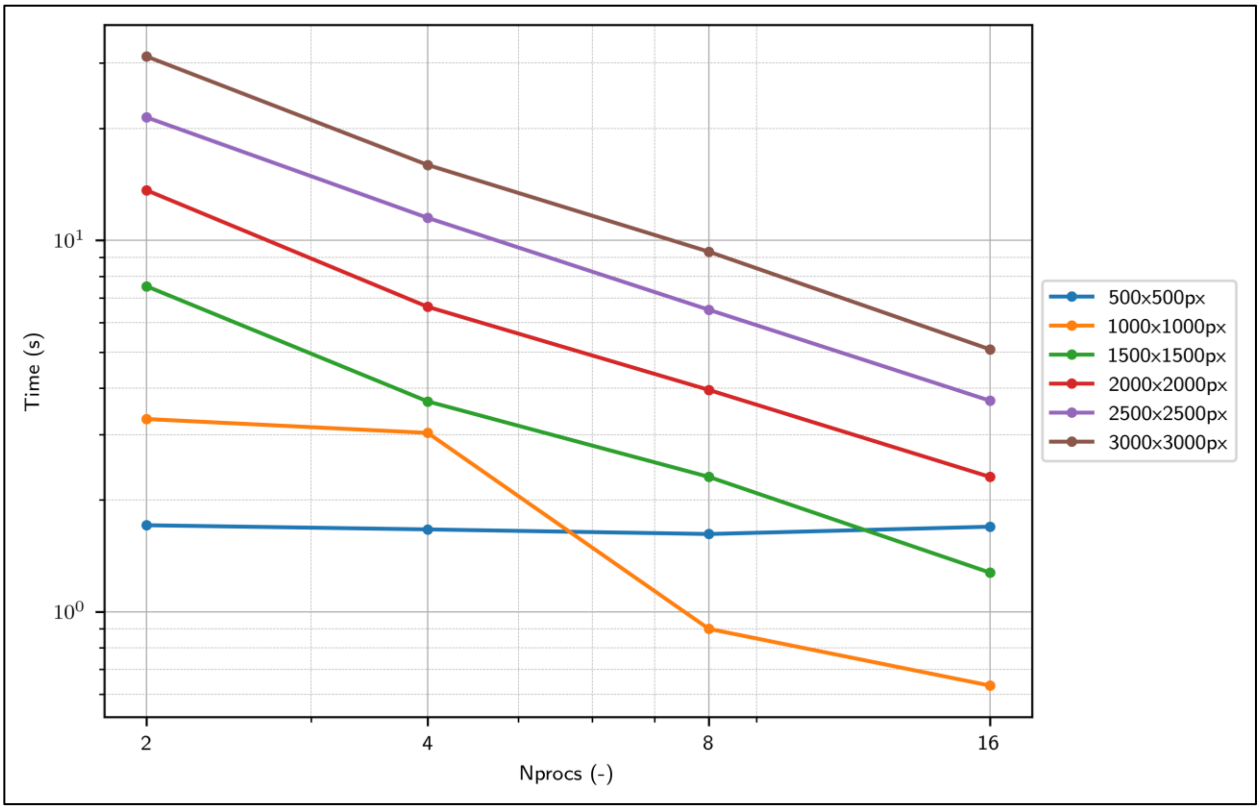


Fig. 2: Speckle rendering scaling graph

Conclusion

In this work, we propose a two-level acceleration of state-of-the-art algorithms to render high-fidelity images for Material Testing 2.0. The first level relies on HPC concepts to reduce computational complexity owing to domain decomposition. The second level incorporates algorithms optimizations for inverse mapping problems. We demonstrate the implemented algorithm scaling on elementary problem. Future work should focus on leveraging GPUs to accelerate calculations on subdomains and on the use of the module on HPC clusters for an advanced assessment of the targeted full-field measurements techniques.

References

[1] F. Pierron, Strain 2023, 59(3), e12434. https://doi.org/10.1111/str.12434
[2] Balcaen, R., Wittevrongel, L., Reu, P.L. et al. Exp Mech 57, 703–718 (2017). https://doi.org/10.1007/s11340-017-0259-1
[3] Sur, F., Blaysat, B. & Grédiac, M. J Math Imaging Vis 60, 634–650 (2018). https://doi.org/10.1007/s10851-017-0779-4