A Radiometric Digital Twin of the Measurement Space for Digital Image Correlation Experiments

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Abstract. The design and evaluation of set-ups for Digital Image Correlation (DIC) measurements is challenging and involves a time-consuming iterative process of evaluation against the metrological requirements of the experiment. Tools suitable for predicting the performance of a DIC set-up, to enable virtual design loops, do not currently exist. Hence, a validated methodology for creating high-fidelity 'Virtual Experiments' (VEs) is presented. The VEs are Digital Twins of physical DIC set-ups, including physically-captured data, which create synthetic images using ray-tracing algorithms and include the effects of the camera system's optical performance, specimen geometry and deformation, test lighting conditions, and the wider measurement environment. A complex component, designed to challenge DIC, is subjected to multiaxial loading. A Digital Twin of the mechanical test is devised and evaluated. The correlated results of the synthetic images produced by the VE are compared with the measurements obtained physically. It is demonstrated that utilising the VE provides a quantitative prediction of the of the DIC set-up's measurement performance.

Introduction. The design, commissioning, and metrological evaluation of Digital Image Correlation (DIC) set-ups is time-consuming and costly. Complex set-ups, which may include multicamera systems, challenging environmental conditions such as high or low temperatures, or large displacements, are becoming increasingly common. Utilising DIC in such scenarios is limited by the specialist knowledge required and iterative nature of design and commissioning. Accordingly, the development cost and time-to-market of new designs increases, particularly in structural applications that would benefit most from DIC, e.g. aerospace and renewable energy.

To reduce both the time and cost associated with devising a complex DIC set-up, a novel methodology for creating a 'Virtual Experiment' (VE), which combines multiple physically-captured data sources to produce a high-fidelity Digital Twin of a DIC set-up, is presented. The Digital Twin can be used to generate synthetic DIC images that include physically-derived specular reflections, optical aberrations, geometries, speckle patterns, and material optical properties. The inclusion of these effects is a significant challenge for existing DIC uncertainty quantification methods [1]. Since these all impact the metrological performance of a DIC system, using a ray-traced rendering engine [2] to include their effects in the simulated VE allows the experimental set-up to be determined in virtual space. Thus, the time-consuming, costly procedure inevitably associated with 'optimising' DIC in physical space is significantly reduced. In an industrial setting, utilising VEs has the potential to drastically increase the tempo of test campaigns and unlock much greater metrological performance for a complex test. It is demonstrated that the lighting conditions, camera position, lens choice, etc., for a complex test can be faithfully represented in a high-fidelity virtual recreation of the measurement space. The potential impact of holistic VEs for the design of DIC set-ups is demonstrated through the definition of a radiometric (i.e., physically-accurate lighting) VE with the simulated results being validated against challenging experimental conditions.

Physical and Virtual Experiments. This workflow is demonstrated using a case study of a geometrically-complex test specimen undergoing multi-axial loading. The test set-up comprises several challenges for a high-quality DIC measurement, including doubly-curved surfaces producing complex specular reflections, self-shadowing, self-occlusion, a multicamera system, large depth-of-field requirements, and a complex stress state including plastic deformation in multiple distinct regions. A Digital Twin of the measurement space and specimen was constructed from physically captured data combined with simulation results. Photogrammetry provided a high-resolution textured mesh of the specimen, including both deviations from nominal geometry due to manufacturing tolerances, and the applied speckle pattern. This allowed for a finite element (FE) model of the test specimen to be constructed using its actual geometry, thereby minimising errors arising from the manufacturing tolerances of a complex surface. This FE model was used to predict the surface displacements and strains of the test specimen when placed under load and is shown in Fig. 1(a).

A textured 3D mesh of a test machine and its surroundings was also captured, allowing for the positioning envelope for the fixtures and cameras to be evaluated. A mirrored sphere, as used in the film industry, was placed in the test machine and imaged; the images were transformed to create 360° maps of lighting intensity. Hence, the generated synthetic images include the non-uniform, high-dynamic range lighting of a real test set-

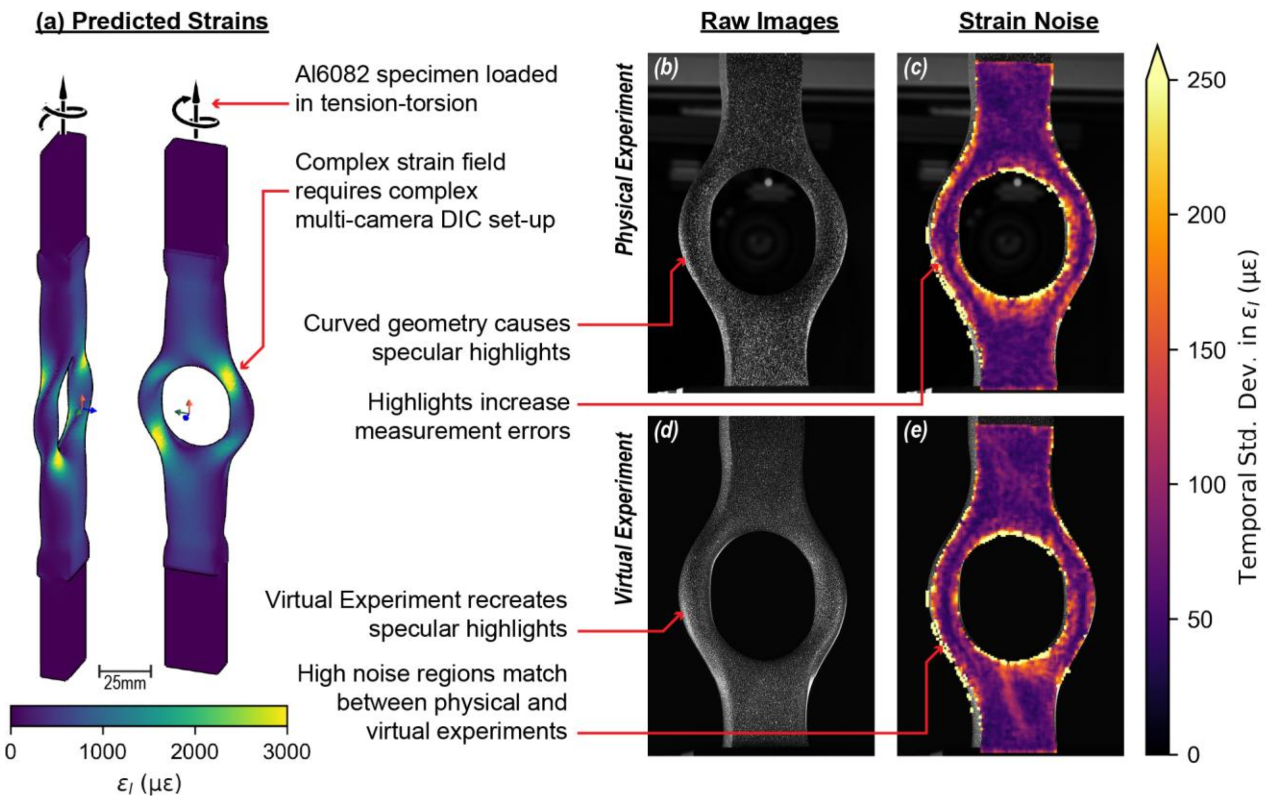

Fig. 1: Finite Element strain prediction (a) for the specimen, with physical images (b) and strain uncertainty quantification (c). A Virtual Experiment yields matching synthetic images (d) and uncertainty prediction (e).

up, which impacts significantly on the measurement performance where specular reflections or shadows occur. The imaging system's optical transfer function was evaluated via slanted-edge analysis, accounting for performance losses due to the softening of the speckle pattern from optical aberrations in the imaging system.

The FE model, captured speckle pattern, test frame representation, lighting, camera positioning and fixturing were combined to create a VE in the computer graphics software package 'Blender', capable of generating synthetic images for different test arrangements and lighting conditions. To demonstrate the utility of VEs for the design of complex DIC systems, synthetic images such as Fig. 1(d) were rendered for the specimen under different loading regimes. These were correlated using a DIC software package and the temporal strain noise was determined. The expected metrological performance of several set-up configurations prior to the experiment being physically set up was predicted, e.g. Fig. 1(e). Corresponding physical tests were also performed, e.g., Fig 1(b), providing full-field strain measurement of the test specimen for a range of multi-axial loading conditions, lighting configurations, and camera positionings. The metrological performance of the set-ups was assessed, and uncertainties and biases in the measured displacements and strains were determined, as shown in Fig 1(c). The outcome is a like-for-like comparison of the metrological performance of the physical set-up and its Digital Twin, thereby providing a methodology for validating the VE.

Conclusion. The novel work described above demonstrates that VEs for evaluating DIC measurement set-ups must include the complete measurement space, including lighting, the geometry of test frames and fixtures, and detailed optical models of the imaging system. Importantly, it is shown that VEs are essential tools for designing and evaluating DIC set-ups in an effective manner, as they enable a virtual evaluation and optimisation of the experimental system without requiring the physical collection of experimental data. The creation of a reliable virtual design loop makes the use of DIC more viable for complex tests by allowing a rapid assessment of measurement system performance without conducting iterative physical experiments. Hence, scale-up of DIC to larger structural testing becomes more efficient and smarter, reducing cost and paving the way for more informative and reliable implementation of DIC in applications of the future.

References

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