A combined optical technique for 360-degree measurement of 3D shape and deformation field of discontinuous surface

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Many applications in industry require non-contact, fast and accurate measurement of both surface profile and deformation field for manufacturing quality control and structural testing purposes. The fringe projection technique has been widely used due to its high accuracy and spatial resolution in measuring shape and out-of-plane displacement fields, but it cannot identify in-plane displacements reliably for surfaces without macroscopic 3D texture. The 3D digital image correlation (DIC) is on the other hand a proven technique for accurately measuring 3D displacement fields, whilst its performance in shape measurement is inferior to that of the fringe projection technique primarily due to its lower spatial resolution. This paper therefore presents a novel technique that combines the strengths of the two well-recognised techniques on one measurement system. A one-camera one-projector system based on fringe projection is used to measure shape and 3D displacement field of surface with complex discontinuities. In order to achieve this, the conventional image correlation technique is modified to cope with discontinuities. The method is then extended to a multi-camera multi-projector system so that complete 360-degree surface profile and 3-D displacement field can be obtained within a unified global coordinate system. The accuracy of the current system has been validated with a plate bending experiment in comparisons with a standard 3D DIC technique and a finite element model.

Accurate 3D shape measurements can be achieved using the simplest arrangement of the current shape measurement system with one camera and one projector. During the measurement process, a sequence of patterns consisting of sinusoidal intensity fringes is projected onto the specimen surface. The position of a scattering point on the surface is encoded as spatial distortions of the fringe patterns in the captured intensity image. Phase estimation and temporal phase unwrapping are applied at each camera pixel independently of its neighbours, from which 3D coordinates of one scattering point per pixel are obtained (see [1] for details). In this way, surfaces with complex geometries and discontinuities can be profiled as easily as simple ones. From the measured 3D coordinates, surface discontinuities (e.g. sudden jumps and holes) can be identified based on the surface gradient, and continuous regions separated by these discontinuities can be segmented and labelled. For the purpose of deformation measurement, this shape measurement process is repeatedly applied to the reference and subsequent deformed states of the object, giving rise to a cloud of about a million points for each state. To establish the correspondence between each pair of points in the reference and a deformed state, the 2D DIC technique is used to track changes of a sub-image centred at the reference point. The specimen surface is prepared with a high-contrast random speckle pattern to aid the matching algorithm. Conventional DIC techniques [2] assume that all pixels within a sub-image lie on the same continuous region, which can be erroneous for sub-images that intersect multiple continuous regions as each region may undergo a different deformation. In this work, the image correlation algorithm is therefore modified so that the correlation is done for each continuous region independently. Finally, 3D displacement vector at any sample point on the reference object can be computed by direct subtraction of its 3D coordinate to that of the corresponding deformed point.

The present measurement system can easily be extended to a multi-camera multi-projector system to achieve 360-degree measurement of both shape and deformation. Due to the modular design, more cameras and/or projectors can be added in order to inspect different parts of the object, since the present calibration technique is able to automatically bring 3D point clouds measured by different camera-projector pairs together into a single global coordinate system (see [3]). Combining 3D displacement fields requires two steps. (i) Displacement fields measured by the same camera (but different projectors) are merged together. Since 2D reference sample points of those pairs are identical, most of their 3D displacements have approximately the same values and thus can be statistically combined to improve the estimated displacement field. (ii) Displacement fields generated by different cameras are automatically transformed into the common global coordinate system.

An experimental specimen is prepared from an aluminium sheet with cut-outs bent into a hat-like profile to introduce challenging discontinuities and viewing shadows. The specimen is clamped at two opposite edges and free at the other edges, and loaded at the centre point by a micrometer-driven displacement ranging from 0mm to 10mm. A system of two cameras and two projectors are used for the measurements. Figure 1 shows an example of 3D displacement fields computed for two camera-projector pairs, which are presented as coloured contours on both 2D images and 3D models. The combined shape and displacement field of the two pairs are presented in Figure 3-a, which demonstrates the ability of this technique to achieve complete 360-degree measurement in the presence of perspective occlusions. The comparison of estimated displacement at the loaded point and the micrometer-driven displacement, as given in Figure 2, shows that the maximum displacement error is about 0.15mm which corresponding to 1 part in 3,500 of the measurement volume. Additionally, the displacement distribution estimated by the present technique agrees very well with that by a standard 3D DIC technique (Figure 3-b) within in directly-loaded region and with the simulated one (Figure 3-c) within the clamped regions.

It has been presented that a standard 2D DIC technique can be integrated into a shape measurement system based on fringe projection at no additional hardware costs to obtain accurate 360-degree measurements of both shape and displacement field of 3D objects with complex discontinuities. As a part of the research project, this technique will be applied to various in-situ structural tests of aircraft wing/fuselage panels at Airbus UK.

References:

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[3] HUNTLEY, J.M., OGUNDANA, T., BURGUETE, R.L. and COGGRAVE, C.R., Large-scale full-field metrology using projected fringes: some challenges and solutions. Proc. SPIE, 6616: 66162C, 2007.

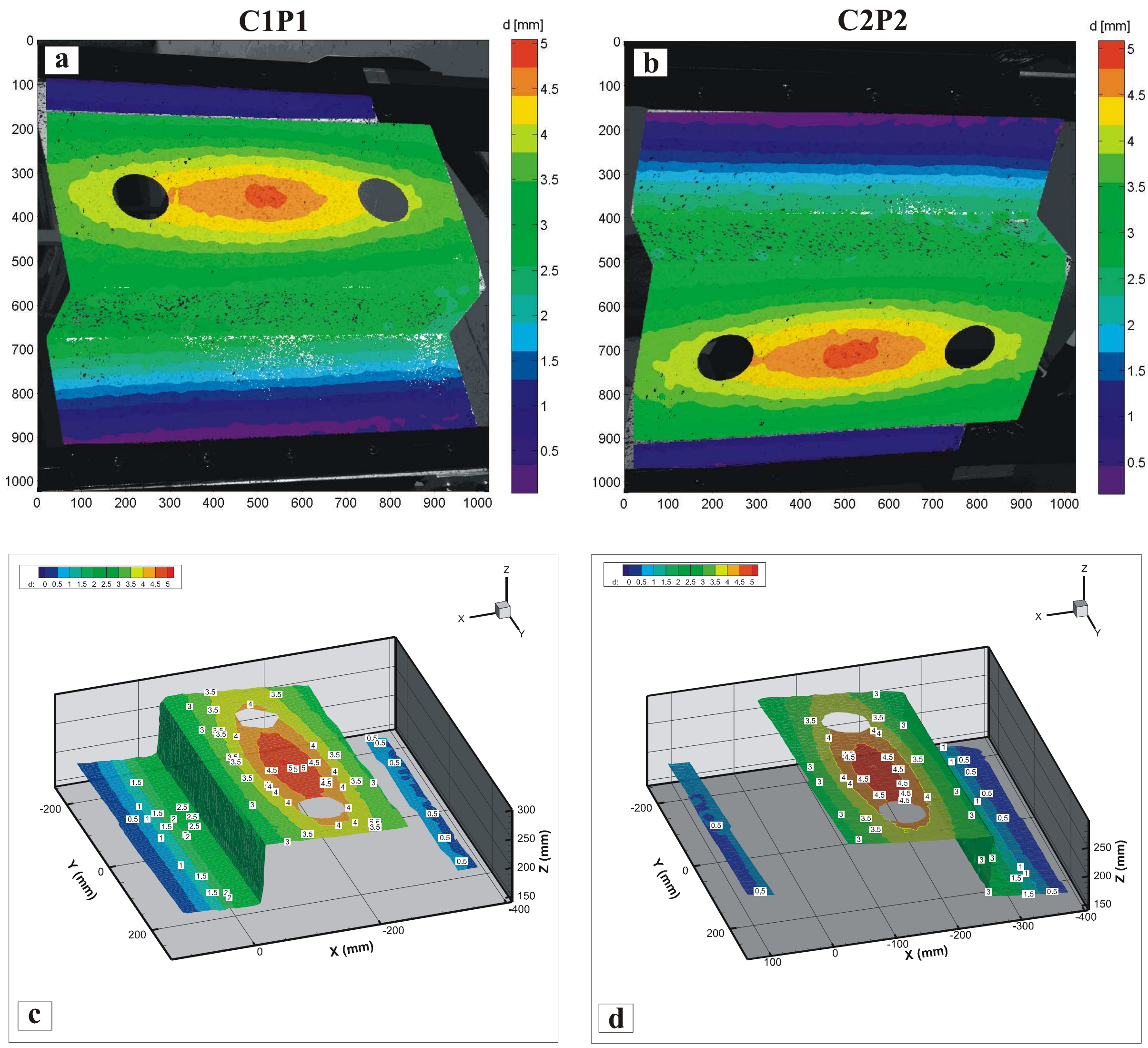

Figure 1: Displacement magnitude fields measured by pairs C1P1 and C2P2, represented on 2D texture images and measured 3D shapes.

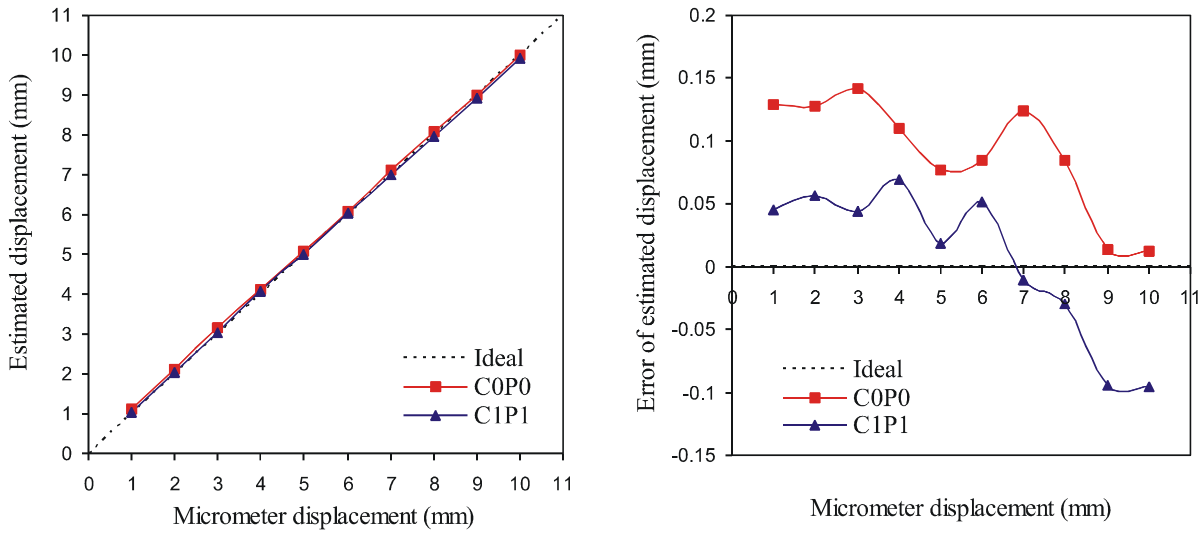

Figure 2: Comparison of estimated displacement at loaded point and micrometer displacement.

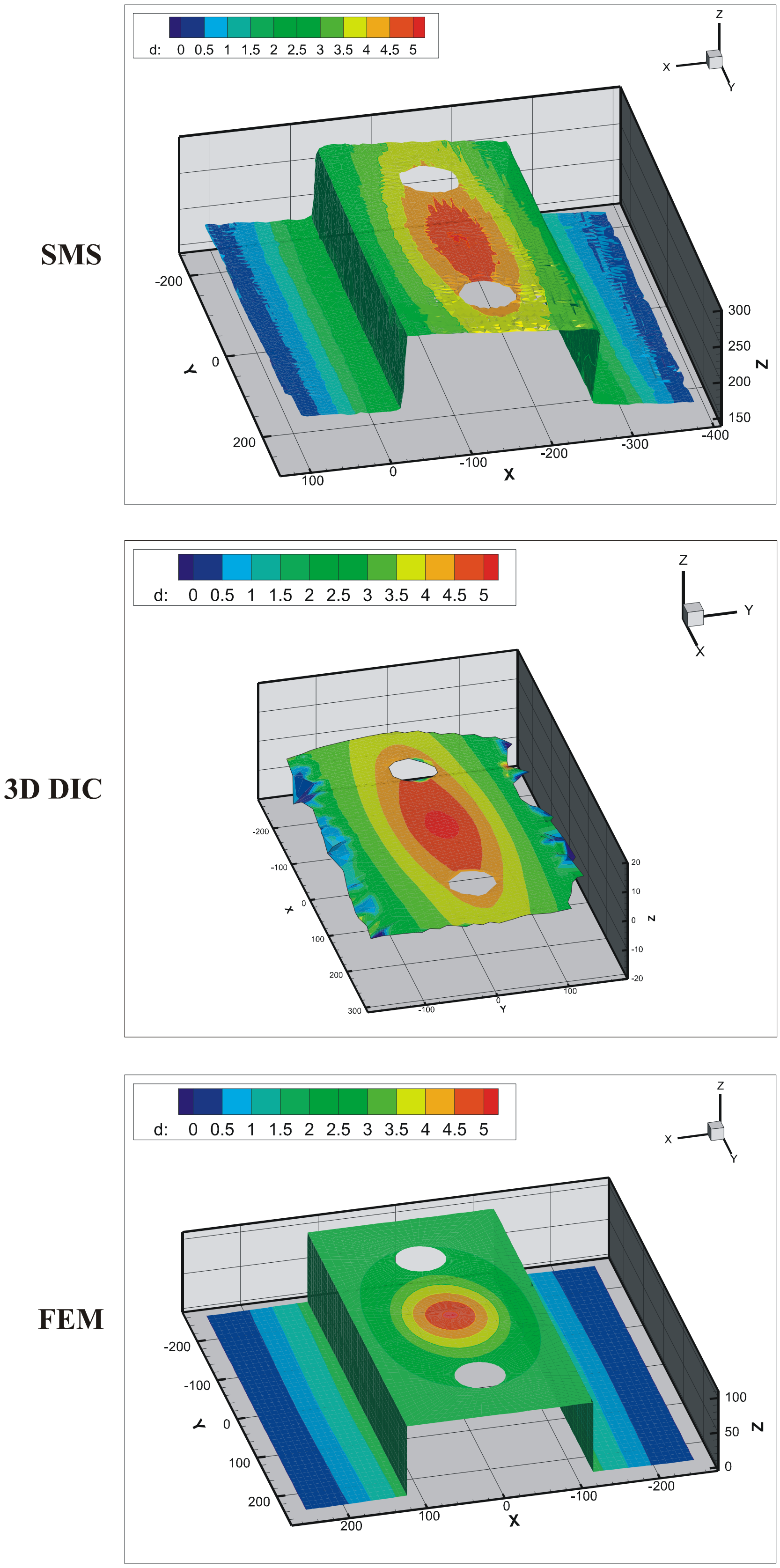

Figure 3: Comparison of 3D displacement fields computed by the present technique (SMS), a 3D DIC technique and a finite element method.