An optical 3D shape and deformation measurement system for the analysis of dental biomaterials

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A measurement system combining multiple optical measurement techniques for the simultaneous determination of 3D shape as well as of micro- and macroscopic deformations is presented. We describe the optimization of critical parameters of the system and compare the measured deformation of a jaw model caused by a loaded dental implant to a finite element analysis.

1 Introduction

Non-destructive analyses of biomaterials in prosthetic dentistry, e.g. dental implants [1], require sensitive measurement techniques for the determination of deformations. An optical 3D shape and deformation measurement system is presented, which combines spatial phase-shifting Electronic Speckle Pattern Interferometry (ESPI) with Digital Speckle Photography (DSP) [2] and photogrammetric 3D shape acquisition by digital image correlation of a projected laser speckle pattern [3][4]. While ESPI is employed to measure deformations in the direction of the optical axis, DSP can be used to determine deformations orthogonal to this axis. The photogrammetric 3D shape acquisition is applied to determine the macroscopic shape and position of the object as well as deformations that exceed the measurement range of ESPI and DSP.

2 Optimization of the measurement system

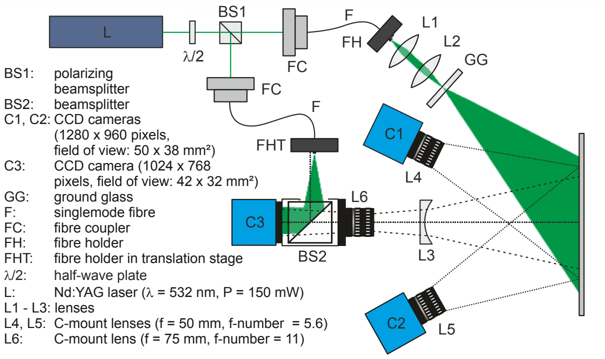

Fig. 1 *The measurement system*

Fig. 1 shows the setup of the measurement system. First, the influence of the size of the projected speckles, the apertures of the cameras (C1, C2) and the filter in the image pre-processing on the 3D data acquisition is investigated (for a subset size of 51 x 51 pixels in the correlation process with subset centers on a 10 pixel grid). The average size of the projected speckles is adjusted by changing the distance between lens L2 and the ground glass. The accuracy of the 3D data acquisition is quantified by measuring a cylinder (radius: 29 mm) and determining the standard deviation of the measured data to a best-fit cylinder.

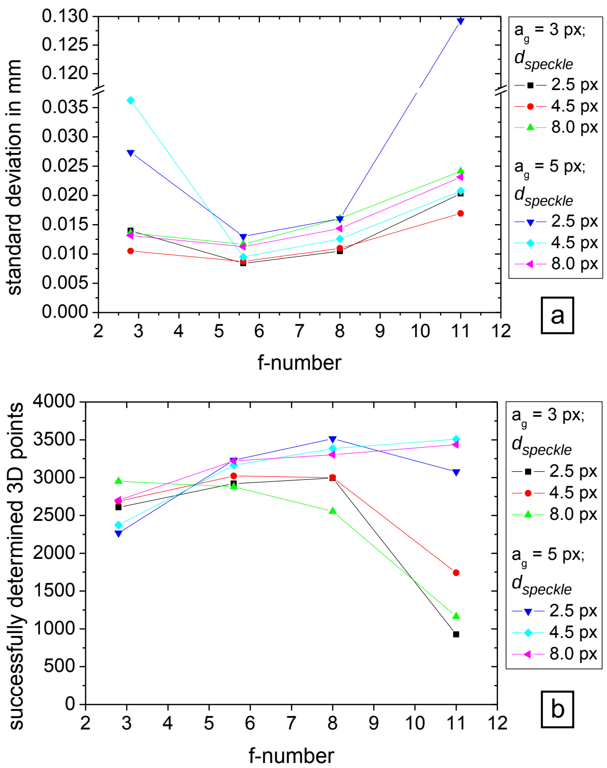

Fig. 2 *(a) Standard deviation to a best-fit cylinder and (b) number of successfully determined 3D points for different f-numbers, average speckle sizes $d_{speckle}$ and kernel sizes a_g of the Gaussian filter in pre-processing*

The results shown in Fig. 2 indicate that an f-number of 5.6, a speckle size of 4.5 pixels and a filter kernel of 5 x 5 pixels offer the best compromise between a high accuracy and a high number of 3D points.

To analyze the influence of the size of the projected speckles and the aperture of the camera (C3) on the ESPI measurement, the noise of the calculated phase difference data for a tilted plate (approx. 10 horizontal fringes result from the tilt) is investigated. The noise is quantified by determining the standard deviation of the original phase difference data to smoothed data (for this purpose a sin-cos-average filter with a kernel of 9 x 3 pixels is applied 30 times).

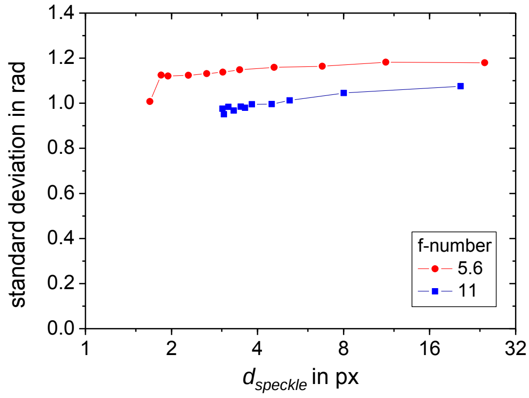

Fig. 3 *Standard deviation of the phase difference data for different f-numbers and average speckle sizes* $d_{speckle}$*. The first data point for each f-number belongs to a measurement without ground glass, L1 and L2*

As shown in Fig. 3, the noise of the phase difference data increases with increasing speckle size. Albeit the increase in noise is nearly negligible, small speckles are preferable. An f-number of 11 yields less noisy data than an f-number of 5.6.

3 Application: Determination of the deformation of a model of a human jaw caused by mechanical loading of an inserted dental implant

a b

Fig. 4 *(a) Model of a jaw (with inserted dental implant). (b) Dental implant*

A cylindrical dental implant (diameter: 3.5 mm, length: 12 mm) made of titanium (Young's modulus: 105 GPa) is inserted into a simplified jaw model (dimensions: 70 x 50 x 30 mm) made of POM (Young's modulus: 2.6 GPa) (Fig. 4). The model is fixed to a metal base plate. A downward load of approx. 50 N is applied to the implant using a force gauge that is mounted to a test stand. The out-of-plane deformation of the model is determined using ESPI, the shape of the model is acquired using the photogrammetric method. The shape is used for precise calculations of the sensitivity vector as well as for visualizing the determined deformation mapped onto a 3D model.

A numerical simulation is carried out using finite element analysis (FEA) software (COMSOL Multiphysics).

The measurement shows a slightly asymmetric deformation of the model with a maximum deformation of approx. 4 µm to the front (Fig. 5 a).

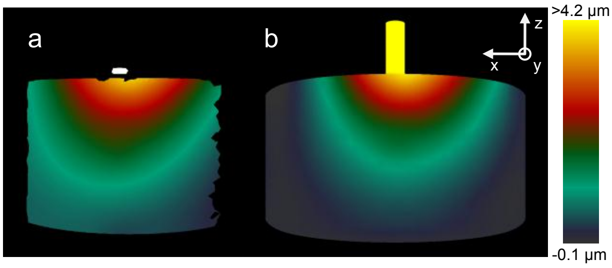

Fig. 5 *(a) Measured deformation in direction of the optical axis of the ESPI system and (b) the result of a FEA*

Finite element analysis yields a consistent result with a fitted force vector **F** = (-4 N, 1.8 N, -50 N) (Fig. 5 b).

4 Conclusion

The illumination with laser speckles generated by a ground glass increases the noise of the phase difference data calculated by ESPI only slightly. Thus, a simultaneous measurement using ESPI and 3D data acquisition by image correlation of a projected laser speckle pattern is unproblematic.

The result of the measurement of the deformation of a jaw model caused by a mechanical loading of an inserted dental implant is in good agreement with the result of a finite element analysis with a fitted force vector.

References

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