Comparison of 3D deformations measured by combined speckle metrology methods with results from numerical simulations

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Introduction

Optical measurement techniques provide the necessary sensitivity to determine microscopic deformations for non-destructive analyses of the mechanical behavior of hard tissue and biomaterials.

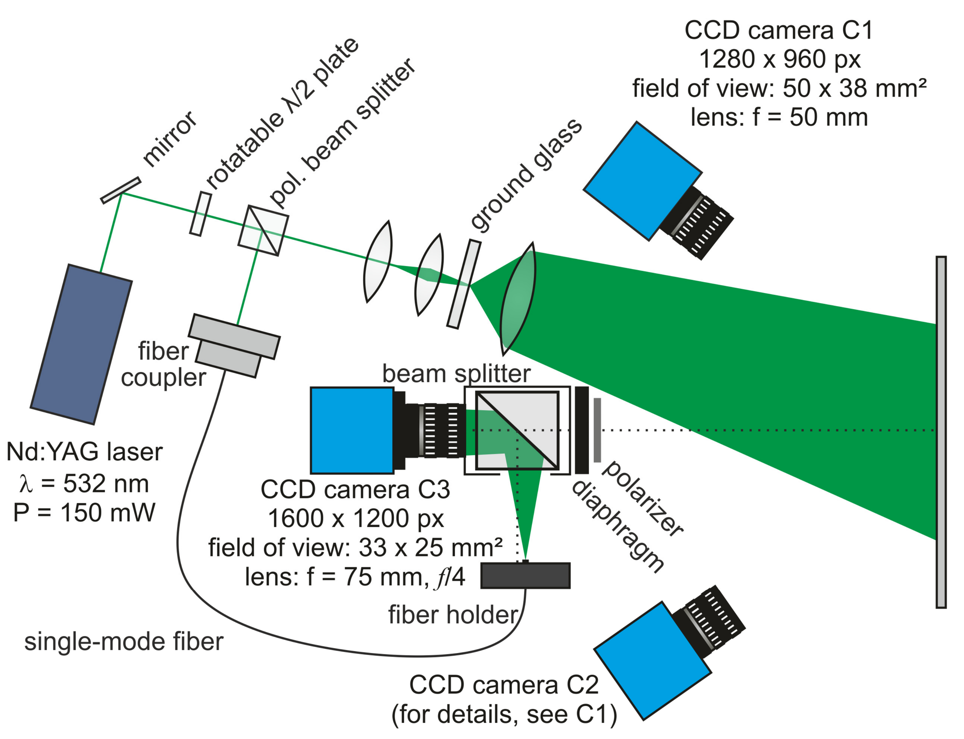
Such problems are usually investigated numerically by finite element analysis. However, the validation and optimization of these simulations require a comparison of numerical results with measured data.

The measurement system proposed for this task combines speckle metrology methods for the acquisition of microscopic and macroscopic 3D deformations as well as of macroscopic shape.

Experimental Setup

Combination of:

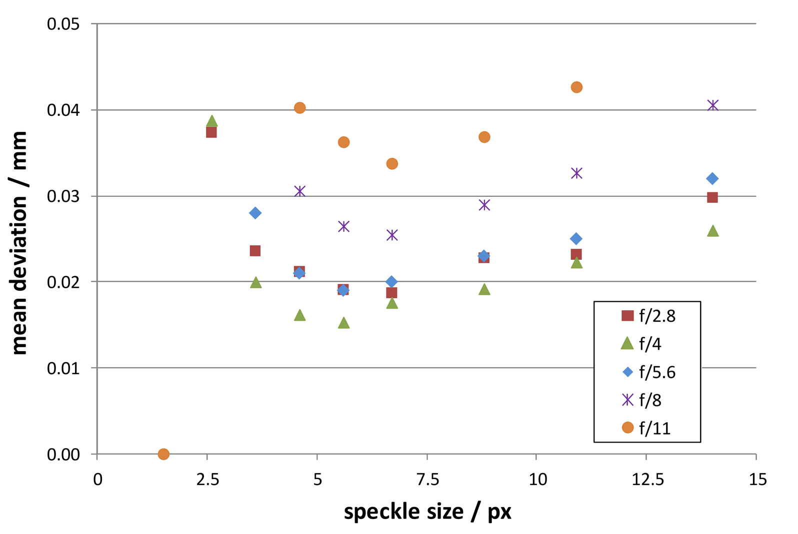
- Photogrammetric 3D shape acquisition by digital image correlation of a projected laser speckle pattern [1]
  ⇒ Macroscopic shape
  ⇒ Macroscopic deformations
- Electronic speckle pattern interferometry (ESPI) and digital speckle photography (DSP), reconstruction of the object wave's phase and intensity distributions by Fourier-transform method [2]
  ⇒ Microscopic 3D deformations



All 3 methods can be applied simultaneously.

Optimization

3D shape acquisition by digital image correlation of a projected speckle pattern

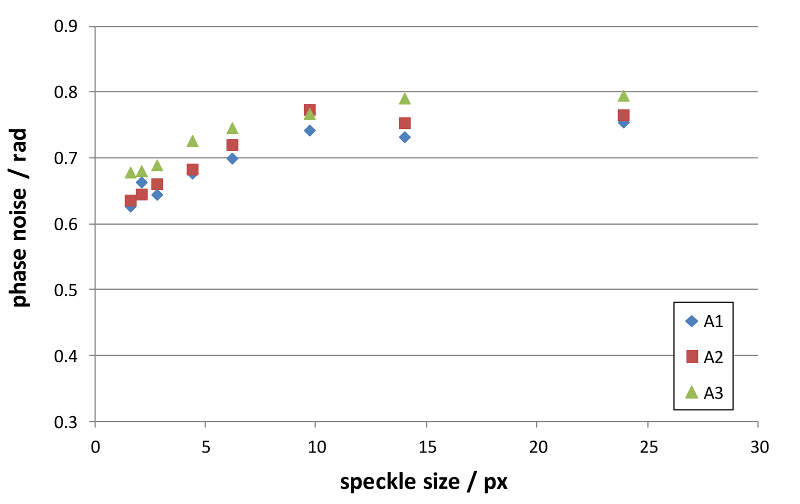


Mean deviation from reference measurement for different f-numbers (cameras C1, C2) and average sizes of projected speckles.

- The precision is quantified by measuring a spherical surface (radius: 15 mm) and determining the mean distance of the measured data to reference data (best-fit of 3D data acquired with a *GOM Atos* fringe projection system).
- Sub-image size in the correlation process: 33 x 33 pixels (px); sub-image centers on a 10 px grid.

⇒ F-numbers from 4 to 5.6 and a speckle size of 7-11 px offer the best compromise between precision and a high number of successfully reconstructed 3D points.

ESPI



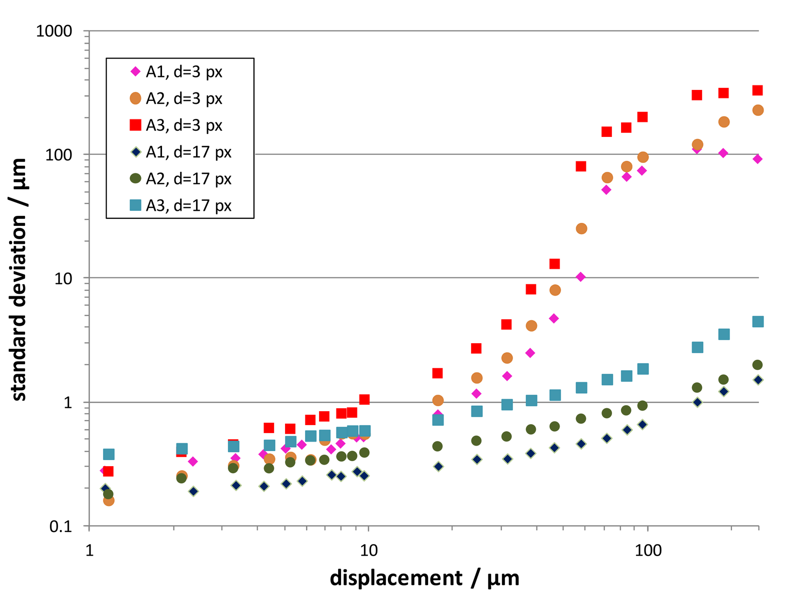
ESPI phase noise for different average sizes of projected speckles and apertures of the diaphragm in front of camera C3 (for A1 the diameter of the sideband's circumcircle amounts to $n_{nyquist}$, for A2 to 0.8 $n_{nyquist}$, for A3 to 0.6 $n_{nyquist}$).

- The quality of the ESPI measurements is characterized by the noise of the wrapped phase difference distribution obtained from a vertically tilted painted metal plate (max. displacement: 6 µm; approx. 23 phase difference fringes modulo 2π).
- The noise is quantified by determining the standard deviation of the original phase difference data to smoothed data (sin-cos-average filter with a kernel of 9 x 3 px, applied 30 times).

⇒ If speckles are projected, they should be small.

⇒ A large aperture of the diaphragm is preferable.

DSP



Standard deviation of the in-plane displacement detected with DSP in dependence on the magnitude of the displacement for different apertures (A1, A2, A3: for description, see above) and sizes of projected speckles *d*.

- The precision is quantified by the standard deviation of measured in-plane-displacements for a coated metal plate that is translated parallel to the image plane of camera C3.
- Sub-image size in the correlation process: 64 x 64 px; sub-image centers on a 64 px grid (391 sub-images per image).

⇒ Larger measurement range for larger projected speckles.

⇒ The largest aperture investigated and projected speckles larger than 5 px yield the lowest standard deviations.

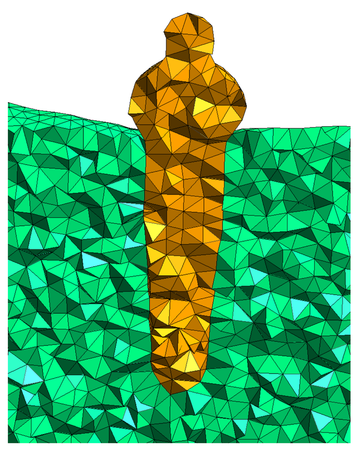
⇒ Higher precision and larger measurement range for homogenous illumination.

Application: Comparison of the simulated deformation of a mandible model due to mechanical loading of an inserted dental implant with measured data

Measurement

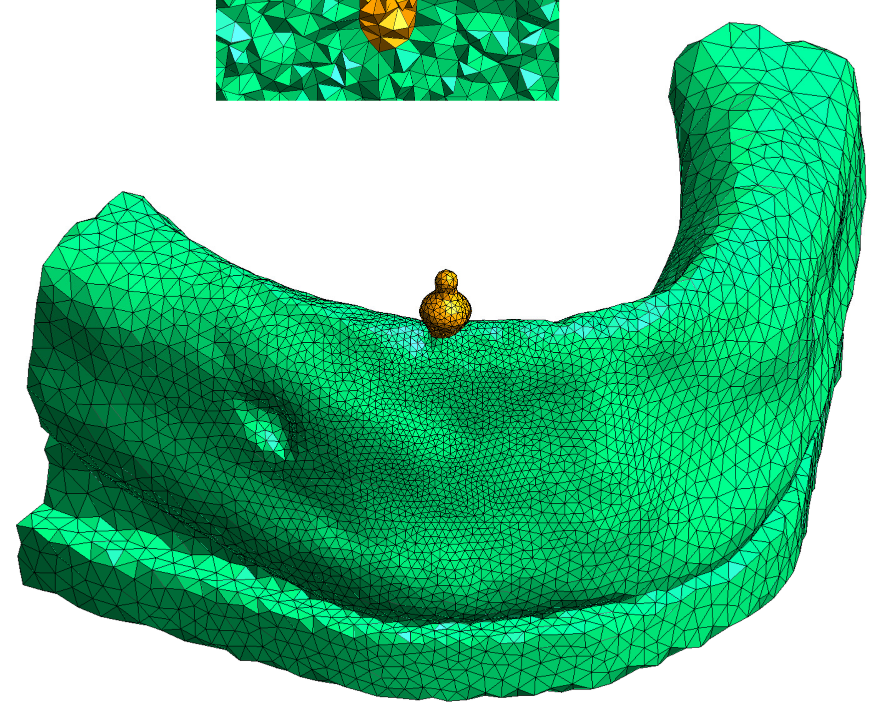
- The mandible model is made of photopolymer (Young's modulus: approx 2.7 GPa) using a 3D printer
- The dental implant (diameter: 2.5 mm, length: 9 mm, titanium, Young's modulus: 105 GPa) is provided with a ball abutment.
- A load of 50 N is applied to the top of the implant with a force gauge mounted to a test stand.
- To achieve maximum sensitivity, the deformation measurement using ESPI and DSP is carried out with homogenous illumination (aperture of the diaphragm in front of camera C3: A1; sub-image size: 64 x 64 px; grid spacing: 64 px).
- For 3D shape acquisition speckles with a diameter of 8.5 px are projected (apertures of cameras C1 and C2: f/4; sub-image size: 53 x 53 px; grid spacing: 26 px).

Simulation

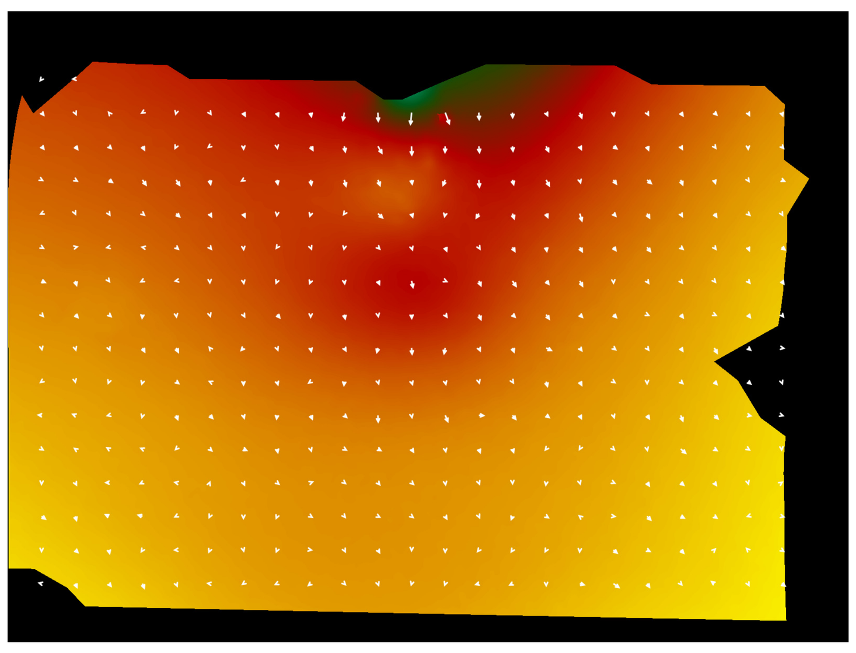


Cross-section through the tetrahedral mesh.

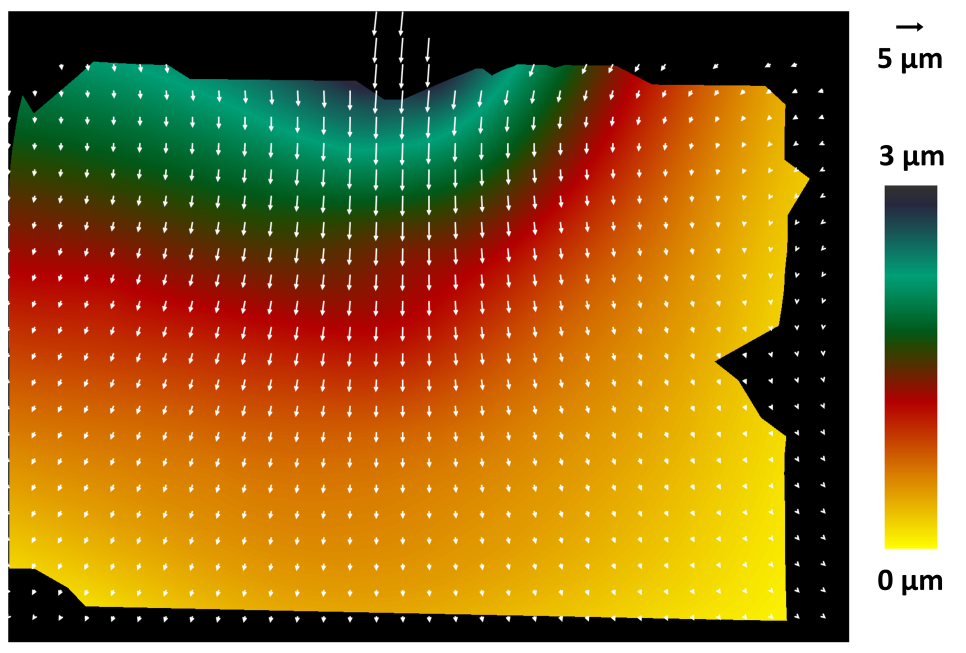
- Transformation of the CAD models of the mandible model and the implant into the coordinate system of the measurement. This is achieved by best-fit registration on the surface determined by 3D shape acquisition.
- Generation of a (second order) tetrahedral mesh using the finite element mesh generator *GMSH*.
- Finite element analysis (FEA) using the FEA application *CalculiX:*
  - Displacement boundary condition: no displacements at the bottom of the model.
  - Load: a load of 50 N is applied to the top of the implant (direction determined photogrammetrically based on the direction of translation of the force gauge).
- Projection of the surface nodes into the image plane of the camera used for ESPI (camera C3).
- Projection of the deformation vectors calculated by FEA on the direction of the optical axis and the image plane of camera C3.



Tetrahedral mesh used for the finite element analysis.



Results of measurement.



Results of finite element analysis.

Results and Discussion

- The method allows for a direct 3D comparison of FE analysis and measurements and reveals the discrepancies.
- While the shape of the predicted deformation is in good agreement with observation, quantitative values differ.
- A possible shortcoming of the simulation could be that in reality, implant and mandible model do not form a single body as it is assumed in the simulation. Furthermore, the assumed contact point between the tip of the force gauge and the ball abutment may be incorrect.

Conclusion

- The measurement system allows the simultaneous acquisition of microscopic and macroscopic 3D deformations as well as of macroscopic shape.
- The size of speckles projected for simultaneous macroscopic shape and deformation measurements shows an opposing effect on the performance of ESPI and DSP. Hence, their optimum size depends on the magnitude and direction of the expected deformations.
- The observed differences between simulated and measured deformations prove the importance of comparative measurements.

References

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