Sensor Fusion Applied To Shape Sensing: Theory and Numerical Proof-of-Concept

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Introduction

Existing shape sensing methods use individual sensor types, determining either strain or displacement well, but not both. More accurate shape sensing could improve load estimation, necessary for accurate life assessment of the structure.

Aim

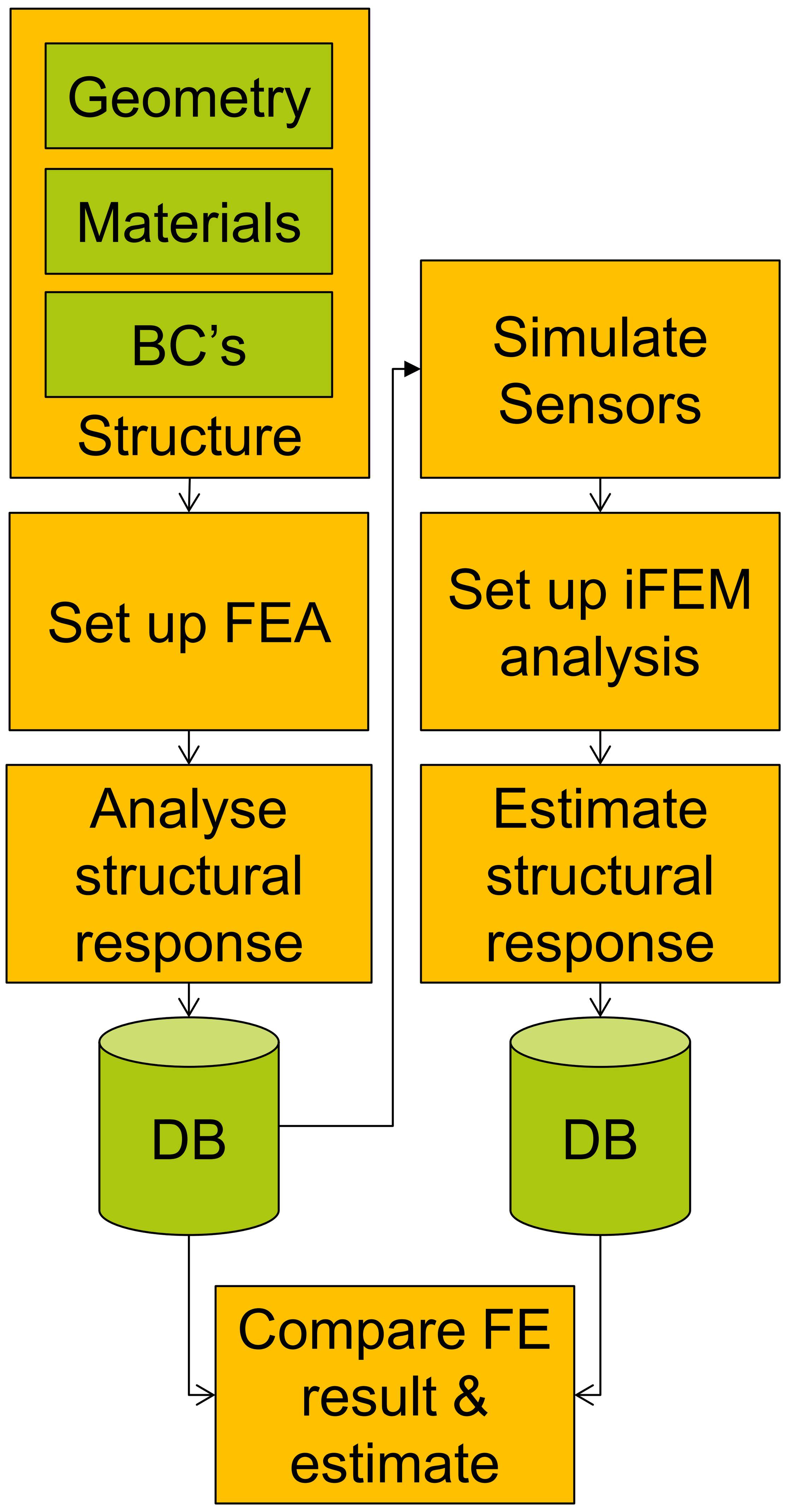
To determine global strain distributions for complex structures with the inverse finite element method (iFEM).

Method

Use the geometry, boundary conditions and material properties to set up an FEA, whose results are used to simulate sensors at random points on the structure. FEA strains and displacements are linearly interpolated to estimate sensor data, which are the input for iFEM. iFEM is based on geometric information of the structure, so it requires no material properties. iFEM minimizes an error functional comparing numerical strains and/or displacements to those obtained from sensors.

$$\mathbf{\Phi} = C_e\|\boldsymbol{e} - \boldsymbol{e}^{\varepsilon}\|^2 + C_d\|\boldsymbol{q} - \boldsymbol{q}^{\varepsilon}\|^2$$

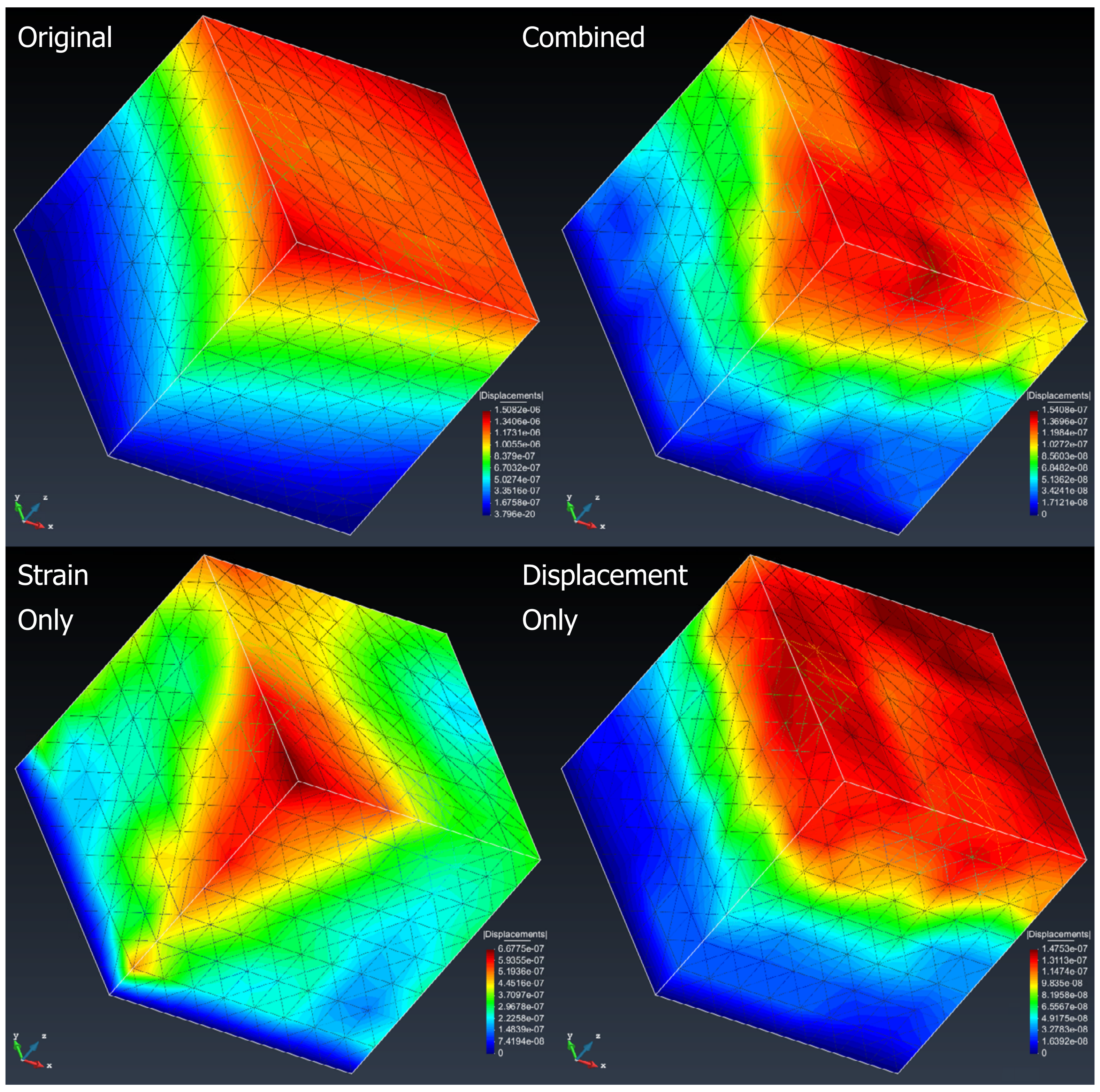
C_e and C_d are weights for the strain and displacement terms, $\boldsymbol{e}$ and $\boldsymbol{q}$ are the numerical values and $\boldsymbol{e}^{\varepsilon}$ and $\boldsymbol{q}^{\varepsilon}$ are the sensor data.



The norms in the error functional are volume integrals over the elements. Quadratic norms are used, as these give the best linear unbiased estimate for sensor data with normally distributed, independent errors. While not necessarily the case, such errors are assumed for now. The functional is minimized by taking its derivative with respect to the structural degrees of freedom (nodal displacements of 20 node hexahedrons). The resulting equations are put into a system for the entire structure, similar to how FEM works. This system is solved for the nodal displacements, which are then used to calculate the elemental strains.

Result

Top left: FEA results, on which the simulated sensor data are based. Top right: iFEM results from 50 simulated strain sensors and 50 simulated displacement sensors, placed randomly. Bottom left: 100 strain sensors. Bottom right: 100 displacement sensors.



Conclusion

The combined results are better than those from only strain data or only displacement data. The overall distribution is similar to the original FEM results. All the iFEM results do differ from the original at some points, likely due to the random sensor locations. The magnitude is also underestimated, likely due to the interpolations, which causes blurring, eliminating extreme values.

Future Work

- Effects of sensor noise/bias
- Evaluating different sensor placement strategies
- Determining optimal sensor combinations
- Method for low frequency, constant amplitude strain variations.

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