

Introduction

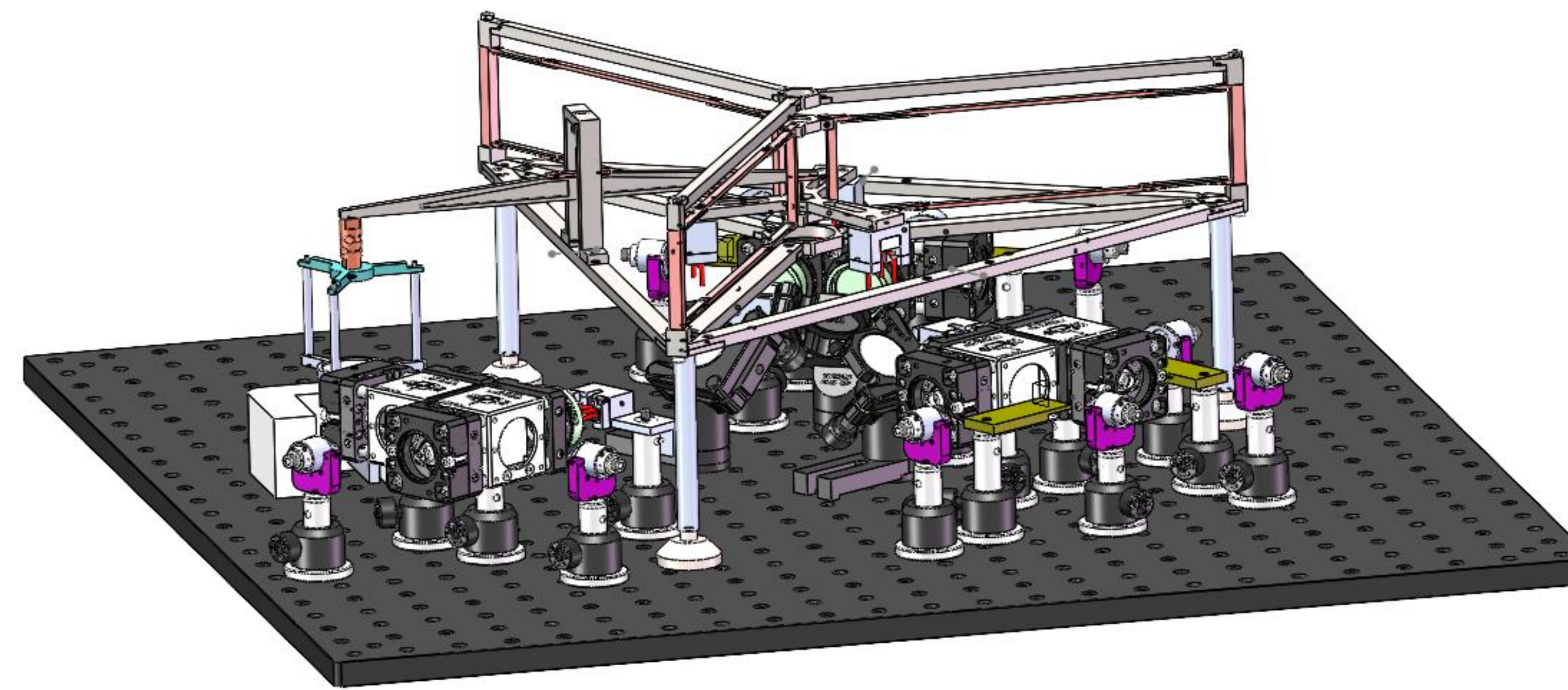
□ Joule Balance is a kilogram realization method based on Planck constant. According to the second key comparison in 2021, The relative measurement uncertainty of the joule balance is $4E-8$; The measurement uncertainty induced by misalignment is $1.7E-8$; which is one of the largest errors in joule balance. Thus, to solve the problem, The goal of this research is designing a new mechanism to reduce misalignment error.

Reciprocal principle

□ In joule balance, the gravitational work of mass in the force measurement mode is equal to the change in electromagnetic energy in the flux difference measurement mode. However, the parasitic forces outside the direction of gravity in force measurement mode do not equate to the electromagnetic energy changes in the parasitic displacements in flux difference measurement mode. Therefore, the alignment errors generate.

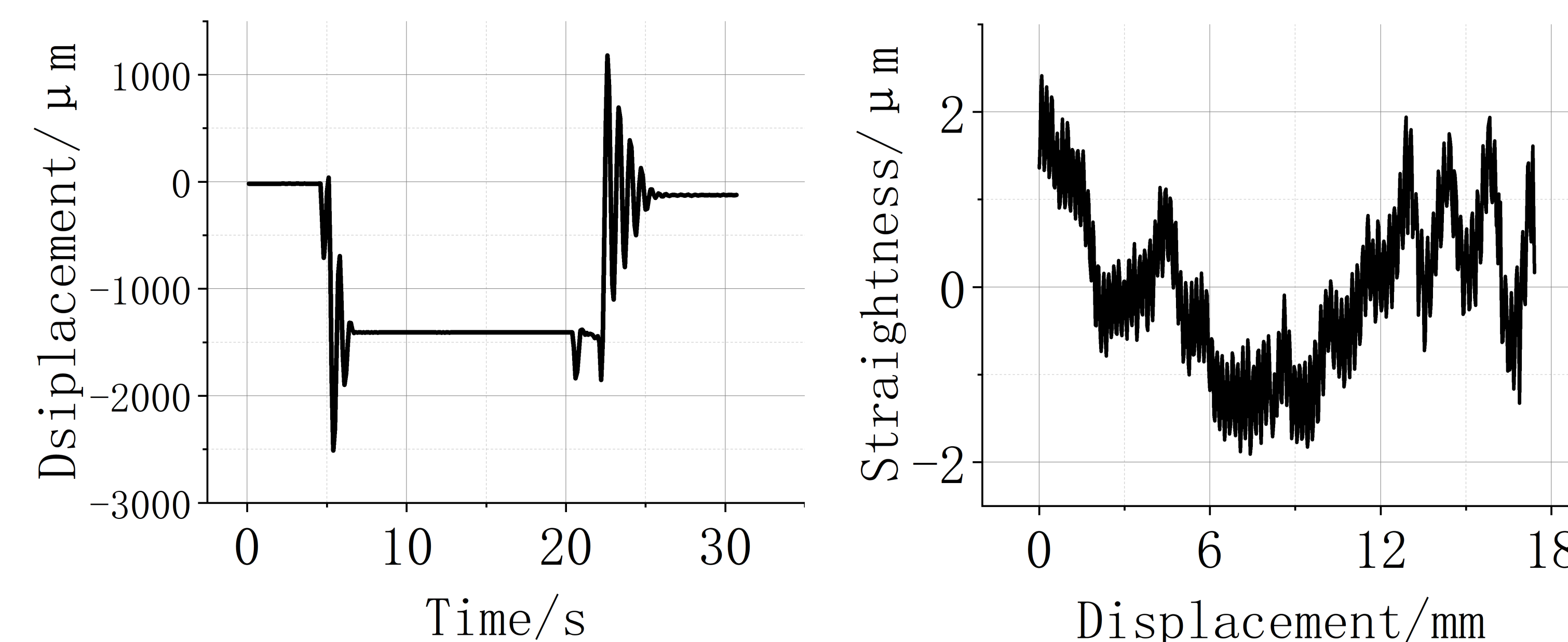
□ For an elastic structure under two different load conditions, the forces and displacements interacting in these conditions exhibit reciprocity. If the force measurement and guidance mechanisms are unified into a single mechanism, the mechanical reciprocity theorem ensures that the forces and displacements interacting in both modes exhibit reciprocity in the same range of motion. Consequently, the parasitic force work and the energy changes in the parasitic displacements become consistent, thereby eliminating alignment errors.

Integrated mechanism of force measurement and guidance



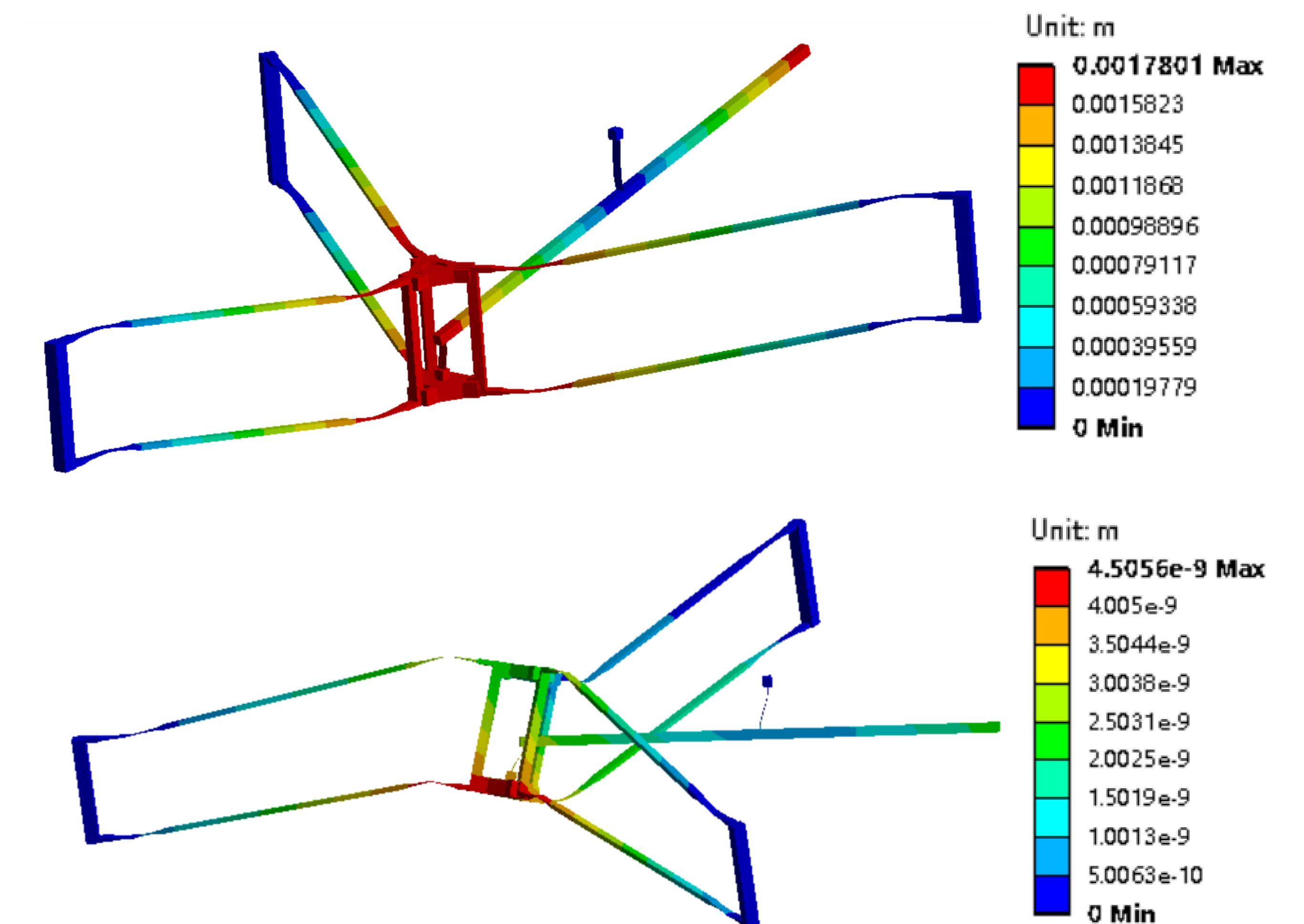
- The integrated mechanism composed of three parallelogram hinges, which are based on elliptical hinges.
- The deformation of the parallelogram hinge is used to achieve a small axial stiffness, and the mutual pulling effect of the three parallelograms is used to achieve a larger off-axial stiffness. Meanwhile, a multi-axis grating interferometer with separated beams is designed to measure deformation of the mechanism. Therefore, the force can be easily measured.

Results



- The force measurement sensitivity of the mechanism is 7.2 mN/mm ; The stroke is 17.2 mm and the straightness is 4.32 μm .

Simulations



- These are the simulated results are axial stiffness 1.1 N/m , off-axis stiffness 2.5 MN/m .
- At the maximum designed stroke (15 mm), the stress is 0.2 times the yield strength. The large stroke, high sensitivity and straightness can be ensured according to the simulations.

Modal analysis of the structure

Modal order	1	2	3	4	5	6
Frequency/Hz	0.7	13.5	25.3	61.2	74.2	107.9

- Because of the static measurement character of joule balance: There is a large difference between the operating frequency and the natural frequency. Thus, we can ensure the stability of the proposed mechanism.

Conclusion

- The mechanism of force measurement and guidance based on reciprocal principle is designed and built. The force measurement sensitivity of the mechanism is 7.2 mN/mm ; within the guiding displacement of 17.2 mm , the straightness is 4.32 μm . With this structure, the uncertainty induced by alignment error can be reduced from $1.7E-8$ to $1.0E-8$.