Picometer topological optical metrology at a million measurements per second

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Abstract: Using a nanowire as example, we experimentally demonstrate all-optical metrology with resolution up to 80 pm and sampling rate up to 1M fps. Here, topologically structured light scattering is used to visualize nanoobject's trajectory with an algorithm discriminating instrumental instabilities and movements of the object relative to its immediate environment.

The use of topologically structured light, featuring phase singularities, is demonstrated to enable non-contact super-resolution metrology with picometre scale precision. Scattering patterns become highly sensitive to subwavelength variations when they interact with these phase singularities, allowing for more information to be extracted from the scattering pattern through deep learning-assisted analysis. However, addressing temporal resolution is equally essential, especially when observing rapid picometer-scale movements, such as transient switching and thermal oscillations of nano-objects. In this study, we present the first realization of high temporal resolution optical localization picometrology, achieving one million measurements per second that discriminate between object movements and environmental instabilities.

Fig. 1 (a & b) provides a glimpse of the evolution of motion capture technology, spanning from capturing a horse in motion to tracking a nanoobject in motion. Here, we use a nanowire as an exemplary nanoobject. The suspended 17-um long, 200-nm wide nanowire with ~100 nm gaps on either side to the supporting membrane is controlled electrostatically by applying voltage ranging from ~0.27 (V) to ~2.45 (V), which causes nanowire displacement between ~100 pm to ~6 nm. A focused 640 nm Gaussian beam illuminates the sample, and a total of 6,000 images of the scattering pattern are captured by a fast camera in 6 ms within a tiny field of view ($6.67\lambda \times 0.83\lambda$, 128 x 16 pixels). The initial dataset of 5,000 images, where the nanowire undergoes repeated displacement while experiencing different environmental instabilities, is used to train a neural network. This neural network learns to distinguish nanowire displacement patterns while ignoring environmental fluctuation. Subsequently, the remaining 1,000 unseen images are evaluated by the trained neural network. As depicted in Fig.1 (c & d), we achieve an average absolute error of ~170 pm at one million measurements per second. Leveraging topologically structured light as an illumination source holds the potential to further enhance the system's performance.

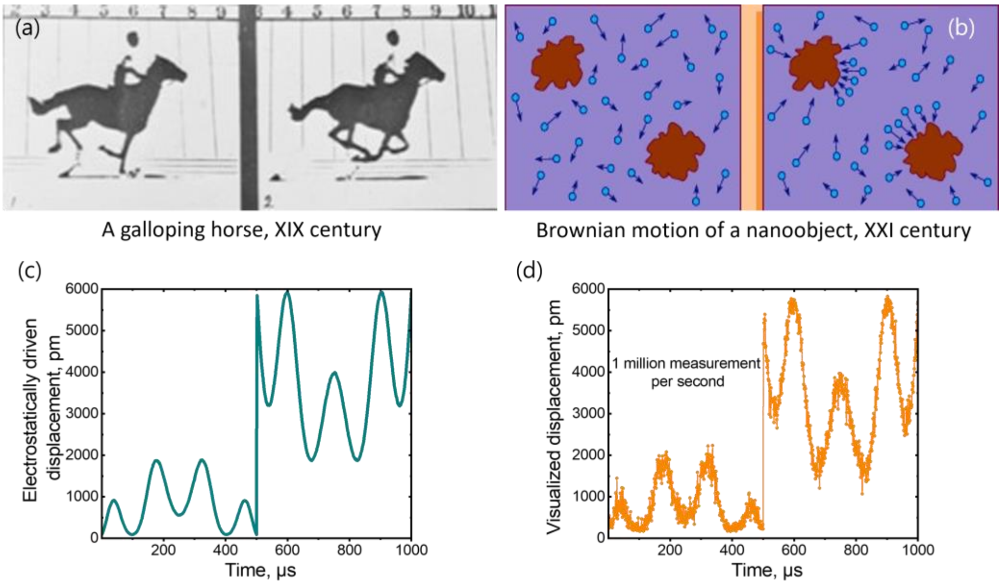

Fig.1 A historical perspective: (a) The horse in motion captured with a daguerreotype camera in 1878. (b) The picometer scale movements of a nanoscale object under thermal forces. Plates (c) and (d) compare the electrostatically driven trajectory of a nanowire with the trajectory visualised by Picometer Topological Optical Metrology at a rate of 1,000,000 measurements per second.

In summary, we demonstrate a non-invasive time-resolved optical super-resolution metrology that can track sub-nanometre movements of the nanowire at down to picometre-level accuracy and capture temporal dynamics at megahertz frequencies. These advancements offer new possibilities for observing and comprehending fundamental processes and interactions in nanostructured systems.