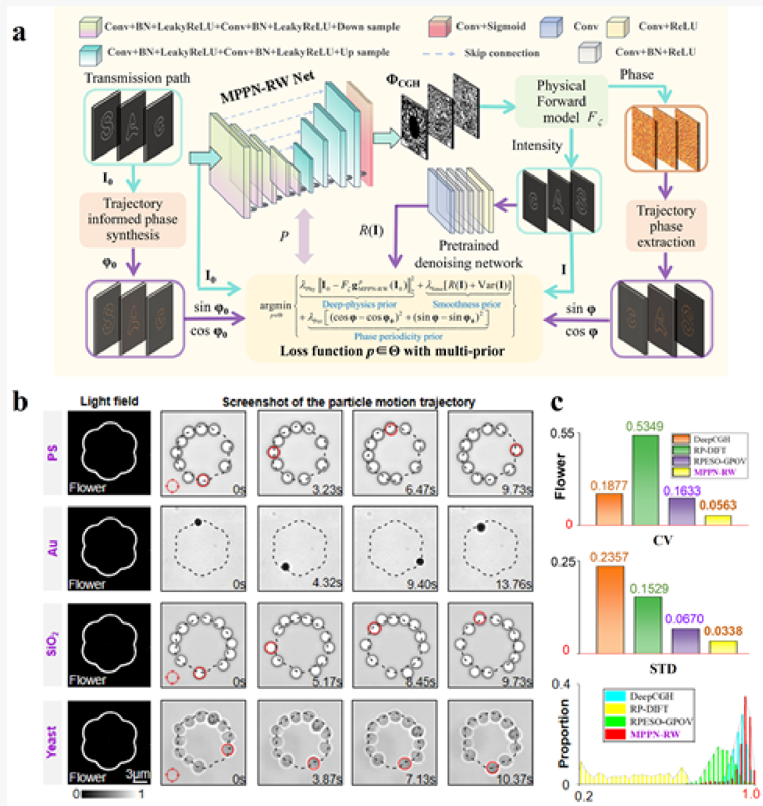
Multi-prior physics-enhanced neural network for high-fidelity arbitrary-path optical particle manipulation

FAYETTEVILLE, GA, UNITED STATES, May 13, 2026 /EINPresswire.com/ -- Programmable optical particle transport based on structured light plays a crucial role in microscale manipulation. Scientists in China have developed a multi-prior physics-enhanced neural network (MPPN-RW) that enables high-fidelity generation of arbitrary optical conveyor belts without training data. This technique allows precise and stable transport of microparticles along complex trajectories, offering new opportunities for optical micromanipulation, targeted delivery, and reconfigurable light-field engineering.



Framework and performance of the MPPN-RW method for optical conveyor belt generation.

As an important form of optical micromanipulation, optical particle transport utilizes phase gradient forces to drive particles along predefined trajectories. Leveraging its advantages of non-contact operation, high precision, and low damage, this technique has found widespread applications in microstructural assembly, biological manipulation, and microscale transport. However, traditional design methods typically rely on explicit parametric equations to construct transport trajectories, which limits their ability to meet the requirements of complex or arbitrary paths. Moreover, modeling approaches based on scalar diffraction theory struggle to accurately describe the vectorial properties of electromagnetic fields under tight focusing conditions, leading to insufficient reconstruction fidelity of optical fields. Although deep learning has shown great potential in optical field modulation, its reliance on large-scale datasets and limited generalization capability still hinder its practical application in optical particle transport. To address these challenges, physics-enhanced neural networks (PN) incorporating physical constraints have emerged as an important development direction. Nevertheless, most existing PN methods rely on a single physical prior, which is insufficient to effectively alleviate the ill-posedness inherent in inverse problems, often resulting in issues such as speckle noise and discontinuous phase distributions in the reconstructed optical conveyor belts.

In a new paper published in Light: Advanced Manufacturing, a research team from the Xi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, and collaborating institutions has proposed a multi-prior physics-enhanced neural network based on Richards–Wolf vector diffraction theory. This framework integrates multiple priors, including physical modeling, phase periodicity, light-field smoothness, and deep image priors, into an untrained neural network to directly reconstruct holographic phase distributions from target light fields. Unlike conventional approaches, the proposed method eliminates the need for training data while ensuring physically accurate modeling of tightly focused vector fields.

Based on this framework, the researchers developed a flexible strategy for generating optical conveyor belts with arbitrary trajectories. By introducing a trajectory-dependent vortex phase modulation mechanism, the method enables continuous phase gradients along complex paths, allowing precise control of particle transport direction and velocity. The generated light fields exhibit highly uniform intensity and smooth phase distributions, which are essential for stable optical force generation and reliable particle manipulation.

The performance of the proposed method was systematically validated through both simulations and experiments. Compared with traditional holographic methods and state-of-the-art deep learning approaches, the new framework significantly improves intensity and phase uniformity, effectively suppresses speckle noise, and enhances energy utilization. Experimental results further demonstrate stable transport of micrometer-scale gold particles along complex trajectories, including high-curvature paths and non-convex geometries, without noticeable stagnation or deviation.

“The method shows excellent scalability and robustness in handling long-distance and highly complex transport paths, such as freeform curves and handwritten patterns. The reconstructed optical fields enable continuous and controlled particle motion over extended spatial ranges while maintaining strong confinement and trajectory fidelity.” they added.

“The proposed technique provides a versatile and efficient platform for high-precision optical manipulation, with potential applications in programmable particle transport, targeted drug delivery, microrobotics, and adaptive optical trapping. It also offers a new pathway for integrating physical modeling and data-driven approaches in structured light-field engineering. ” the scientists forecast.

References

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