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Line optical tweezers as controllable micromachines: techniques and emerging trends

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In the past three decades, the technology of optical tweezers has made significant contributions in various scientific areas, including optics, photonics, and nanosciences. Breakthroughs include manipulating particles in both static and dynamic ways, particle sorting, and constructing controllable micromachines. Advances in shaping and controlling the laser beam profile enable control over the position and location of the trap, which has many possible applications. A line optical tweezer (LOT) can be created by rapidly moving a spot optical tweezer using a tool such as a galvanometer mirror or an acousto-optic modulator. By manipulating the intensity profile along the beam line to be asymmetric or non-uniform, the technique can be adapted to various specific applications. Among the many exciting applications of line optical tweezers, in this work, we discuss in detail applications of LOT, including probing colloidal interactions, transporting and sorting of colloidal microspheres, self-propelled motions, trapping anisotropic particles, exploring colloidal interactions at fluid-fluid interfaces, and building optical thermal ratchets. We further discuss prospective applications in each of these areas of soft matter, including polymeric and biological soft materials.

Introduction

With the advent of optical tweezers, which use a highly focused laser beam to control positions of micron-sized dielectric particles in three dimensions, a wealth of novel measurements in the fields of biophysics and colloidal physics became possible.[1–5] Optical tweezers can be used to trap micron-sized particles and exert controllable forces on the order of picoNewtons; this is the typical force range to study mechanical properties of biological systems, such as the structure and dynamics of biological molecules;[6–10] assemblies and cells;[11–17] liposomes as models of cell membranes;[18] to manipulate colloidal systems;[19,20] and to study structure and interactions within solutions and gels.[21–24]

Applications of optical tweezers have progressed further through the ability to direct and shape the profile of the focused laser spot(s). Various options exist for doing this, including beam steering with mirrors, using feedback to create virtual potentials,[25] and spatially modifying the amplitude and/or phase of the laser beam to split the beam in different directions and focal spots.[26–31] An interesting class of such optical tweezers is Line Optical Tweezers (LOT). Particles are trapped in two dimensions and are constrained to move along a line, rather than being confined in all three dimensions. Even within this simple manipulation of the optical field, microscopic particles have complicated translational and rotational motions. While reviews have discussed general optical trap shaping,[26,32] the design and applications of LOT have not been a focus. In this perspective, we aim to present a brief overview of the latest progress on fundamentals and applications of line optical tweezers. The focus is on the applications of LOT to colloidal interactions and self-assembly, transport and funnelling of microspheres, and self-propelled cyclic motions of microspheres. In each section, we propose future directions that could extend the applications of these controllable micromachines in various areas of soft matter, biological materials, and colloidal physics.

Instrumental designs

To create LOT, people have explored various methods, which can be categorized into "non-scanning" and "scanning" methods, depending on whether the light beam is physically scanned within the sample. A simple and perhaps the least expensive method is to insert a cylindrical lens in the optical path of the optical tweezers system, providing a non-scanning approach. As shown schematically in Table 1, the cylindrical lens generates an elliptical trapping beam, approximating a line trap.[33–35] Dasgupta *et al.*[33]

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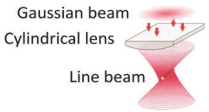
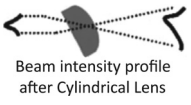
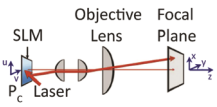
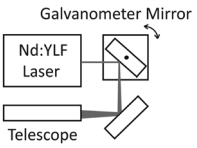
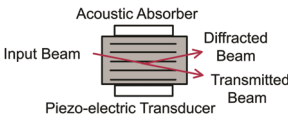
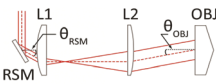
Table 1 Various designs of line optical tweezers

Types	Scanning	Schematic	Ref.
Cylindrical lens	No		34
Tilted cylindrical lens	No		35
Spatial light modulator	No		32,48,81
Galvanometer mirror	Yes		37–39
Acousto-optic deflector	Yes		42,44
Resonant scanning mirror	Yes		47

created a straightforward and controllable approach for rotation of biological cells and non-spherical intra-cellular objects inside a cell, directly by rotating the cylindrical lens. Another interesting modification of LOT based on the cylindrical lens is to position the lens in a tilted manner such that the originally symmetrical Gaussian profile of the laser beam becomes non-uniform with an increasing intensity profile (Table 1). One could take advantage of the non-uniform intensity because the asymmetric beam profile makes trapped particles such as colloidal particles[35] or nanorods[36] translate along the line trap, thereby creating an "optical travelator".[35] Alternatively, an approach known as phase-shape modulation using a spatial light modulator (SLM)[32] can be used to provide a simple technique for manipulation and assembly of one-dimensional nanostructures.

Another large group of LOTs have been formed by rapidly scanning an optical trap with a motorized mirror[37–41] or acousto-optic deflector (AOD)[42–46] (Table 1). Using these methods, one can generate time-shared optical traps that essentially create a rod of light in which particles can freely diffuse along the scan direction while being strongly confined in the other two directions. The advantage of AODs compared with oscillating mirrors is faster position measurements with higher time resolution, suitable for dynamic measurements up to 40 kHz.[42] As another example, Rogers and Crocker[47] have shown that with a combination of a mirror and AOD, spatial resolution can reach as small as 1 nm, which is well-suited to measure, for instance, pair interactions between colloidal particles.

Creating a line tweezer with uniform intensity and uniform trap potential is challenging. Some groups suggested a specific design of a line trap that creates linear optical intensity and potential along the line tweezers by taking into account the counter-acting intensity profile.[48,49]

All the above methods create line traps perpendicular to the optical axis. Alternatively, line traps along the optical axis can be created using a Bessel beam.[50,51] With a beam profile of a bright spot surrounded by concentric fringes, the Bessel beam exhibits an extended propagation distance and maintains its focus along a line. Practically, this can be directly used to create LOT along the optical axis.

To construct and perform experiments with LOTs, researchers may face some technical challenges. For instance, LOTs have low tolerance for longitudinal spherical aberration (LSA). The cumulative LSA is contributed from each lens in the light path as well as the microscope objective.[52] Because the trap stiffness is compromised due to the focal spot being extended, the LSA results in non-stable trapping of particles, especially higher-index particles. To lower the LSA, one can increase the focal length of the optical train, or alter the refractive index of the immersion oil, which has similar effects with having a refractive slab in the converging beam path.[52]

For many applications of LOT, detection and tracking of particle motion is essential. For single particles trapped in a LOT, position detection could in principle be possible using a second detection laser, as is done in some conventional optical tweezers set-ups.[53] This would provide a high-bandwidth readout of particle position. Brownian motion of a single trapped particle, as detected using the deflection of the trapping laser on a position-sensitive photodiode, could also be used to calibrate the trap stiffness.[30] However, when many particles are trapped, laser-based detection methods become impractical. Instead, LOT

implementations have used particle imaging and analysis. Charge coupled device (CCD) cameras have been widely used in LOT imaging systems. In contrast, complementary metal oxide semiconductor (CMOS) cameras are relatively less expensive; however, they can achieve comparable signal-to-noise ratio and dynamic range at near infrared wavelengths.[52] The imaging speed can be further improved by reducing the region of interest, and the spatial resolution can be improved by providing an adjustable magnification through relay optics between the microscope and camera. Imaging with high-speed cameras can be sufficient to calibrate trap stiffnesses using power spectral analysis, and can achieve particle position resolution on the order of nanometers.[54]

Probing colloidal interactions and self-assembly

Pairwise interactions

With a spatial resolution on the order of nanometers, entropic effects in interactions between hard-sphere colloids can be resolved. In 1998, Verma *et al.* directly measured the interaction potential between two particles in DNA polymer solutions using LOT.[55] In 1999, Crocker *et al.* used LOT to measure interactions between two colloidal particles, which were free to diffuse in one direction (longitudinal axis) while strongly confined in the two directions perpendicular to the line axis.[37] Position fluctuations of the particles can be measured and used to map out pair interactions. Using video microscopy, Crocker *et al.* measured the probability, $P(r)$, of finding the two particles diffusing along the line at a given separation r and measured the pair interaction energy, $F(r)$, using Boltzmann equation $P(r) \sim \exp[-F(r)/(k_BT)]$. This approach enabled mapping the functional form of the attractive potential with nanometer spatial resolution.

Direct interactions such as electrostatic and van der Waals are effective over distances comparable with the particle diameter. In contrast, indirect interactions, such as hydrodynamic coupling, reach lengths on the order several particle diameters and often control the kinetics of the colloidal system's reactions. Trankle *et al.*[44] used LOT to study the hydrodynamic coupling between colloidal particles, and they demonstrated that salt concentration affects the interaction forces and mean contact times between particles. They further investigated the effect of confinement on binding probability and contact times.[56]

Colloidal interactions induced by molecular bridges such as DNA hybridization have been utilized to form ordered crystal lattices and various other self-assembled structures.[57–59] In this area, LOT has been used to characterize DNA-induced pair interactions and to quantify the binding/unbinding kinetics as a function of DNA density and strength of pair interactions (Fig. 1a). For instance, hybridizing DNA strands with 7-basepair complementary sequences results in an average bound lifetime of ~0.1–1 s depending on DNA density on the surface of microspheres. This approach could be applied to investigate binding and unbinding kinetics in a wide range of other biomolecular systems known to interact. To do so, one would coat colloidal particles with the molecules of interest and characterize their pair interactions as a function of the density of the biomolecules on the surface of microspheres as microspheres randomly diffuse within LOT. This information could complement more active schemes of determining single-molecule unbinding kinetics under force,[60] which generally require reasonably long lifetimes, or inferring unbinding rates of transient interactions from the frequency-dependent shear moduli determined *via* optical-tweezers microrheology.[11,24]

LOT has also been used to investigate how proteins affect interactions between lipid bilayers. Kong and Parthasarathy[61,62] used LOT to measure interactions between pairs of colloidal particles coated with lipid bilayers, some of which included membrane proteins (Fig. 1b). Membrane composition defines the magnitude and the range of particle interactions.[61] Thus,

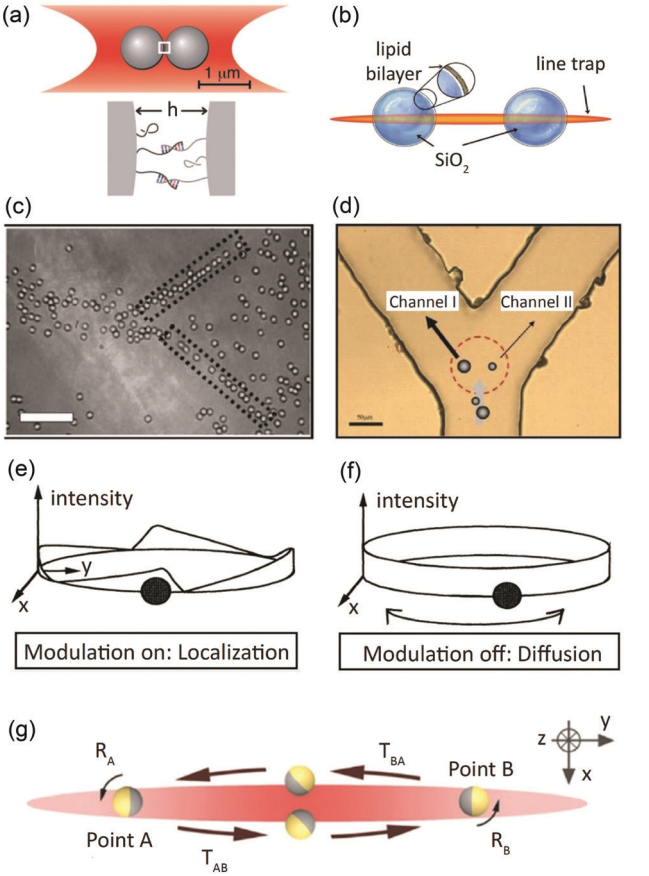


Fig. 1 (a) Two microspheres held in LOT transiently bind together due to complementary, single-stranded DNA strands grafted to their surfaces (box).[59] (b) Two membrane-functionalized silica microspheres in LOT.[61] (c) An experiment showing herding of polystyrene microspheres using two optical travellators.[35] (d) Micrograph of a microfluidic system used for optical sorting of particles based on their sizes using dual-channel LOT.[83] (e) Directed motion of a microsphere in a thermal ratchet made by spatially asymmetric modulation of the beam intensity in a circular pattern. (f) A particle is diffusing freely in one dimension while confined in a circle by a scanning optical trap.[41] (g) Roundtrip motion of a Janus particle in LOT. The particle is made from a polystyrene microsphere half-coated with thin gold film;[34] note that the intensity is weaker at the ends of the line than in the middle, thereby creating a gradient along the line.

it could be used to control the assembly of particles into clusters or other superstructures.

Higher-order colloidal assembly

In the area of self-assembling colloidal systems, LOT can be used to map "folding" pathways to a low-energy stable structure. For instance, in a system with an attractive potential between colloidal particles, LOT can be used to align colloidal particles; by turning off the trap, one can capture the evolution of structure from a linear arrangement to a lower-energy folded structure.[63] In a colloidal system with two or more types of interactions, the free energy landscape of folding becomes very complicated. For example, in a system with dipolar and depletion interactions, if the dipoles are strong, the energetically favoured state is the linear chain of colloidal particles. In contrast, in a system with weak dipoles and strong depletion interactions, the energetically favoured state is a compact cluster. In a condition where interactions are comparable, the final equilibrium state is unclear;[63] in this case, LOT provides a means to visualize and capture the colloid dynamical rearrangements and study this folding landscape.

The growth of colloidal assemblies has also been investigated, making use of LOT. For example, Liu and Li[64] crystallized microspheres in 1D and visualized the structure growth arising from further particle addition. Using LOT, they were able to study 1D (linear) growth and 2D (lateral) growth (after turning off the potential) that resulted from interactions between microparticles and the line optical field. They also observed dynamic rearrangement of the existing structure from 1D to 2D in the LOT. This study is a direct observation of the crystallization process of colloidal particles. It can further be used to explore a wide range of scientific questions, such as the formation of dislocations within a crystal, dynamics of crystal formation, the relaxation time scale of a crystal reaching a steady state, and it can even be used to fabricate long-range ordered crystals in a controlled manner.

Trapping anisotropic particles

Optical tweezers have also been utilized for trapping anisotropic nanostructures, including nanowires and carbon nanotubes.[65] In particular, LOT was used by Yu *et al.*[36] to manipulate and assemble one-dimensional CuO nanorods. This technique is capable of forming a more complicated network of nanorods and, hence, may apply to the fabrication of nanoelectronic devices. This example suggests that LOT can precisely and effectively be used to control the motion, position, and direction of nanorods and facilitate their orientational arrangements in the fabrication of nanostructural devices.

In biological applications, optical tweezers have been used to trap and manipulate non-spherical particles such as viruses, bacteria, and red blood cells.[16,66–68] LOT could be used to extend this work and align rod-like biological structures such as microtubules along the beam. Previously, microtubules have been held by two trapped beads attached to the microtubule.[69] The advantage of LOT over this method is that there is no need for attached microsphere "handles" on the microtubule. Such an approach could provide a means of monitoring molecular motor motion along tracks not fixed to a substrate.[69] It could also be used for similar rod-like tracks, such as collagen fibrils, along which matrix-metalloproteases (MMPs) exhibit directional motion.[70,71]

Colloids at a fluid–fluid interface

Colloidal particles absorbed at a fluid-fluid interface modify interfacial properties such as interfacial tension, rheology, and permeability.[72–75] Interfacial microrheology is a promising approach for studying local rheological properties of interfaces over a broad range of frequencies, regardless of the heterogeneity.[76] In this approach, the motion of particles trapped at the interface is used to extract rheological properties of the interface.[76] What LOT offers to this system is its ability to confine particles at the interface while allowing them to move freely along the longitudinal optical axis of the LOT.

We propose that LOT could be used to quantify particle interactions at a fluid-fluid interface. Understanding these interactions is suggested to be an important step toward the rational design of colloidal assemblies.[77] There are still many puzzling observations of the interactions of colloidal particles at an interface, for which new experiments are needed. For example, Nikolaides *et al.*[78] observed long-range attraction between like-charge particles; they proposed that this is due to the deformation of the interface by the electric field of the charged particles, but the mechanism is still perplexing. Are any other capillary interactions playing a role? What is the effect of heterogeneity on the interactions between particles at the interface? These are questions that we believe LOT can be utilized to address.

In the context of interface permeability, if LOT were instead aligned such that the longitudinal optical axis is perpendicular to the interface, LOT could be used to confine motions of the trapped particle in a line across the interface. While such an approach has not yet been tested, it has the potential to provide detailed information about partition coefficients and dynamics of particles crossing the liquid–liquid interface. Furthermore, it could be applied for quantitative analysis of transported drug uptake across a lipid membrane of a vesicle.

Transporting and sorting of microspheres

Optical traps have been implemented in assays to transport and sort microspheres. Most successful methods exploit holographic methods in which a single spot of the trap is transformed into a desired trap array, so-called holographic optical tweezers (HOT).[79–82] Alternatively, LOT can be used for optical transport and sorting; in principle, it can also be easier to construct LOT than HOT for optical sorting applications.

One method to produce directed motion along a line optical trap implements an asymmetric light intensity distribution to

generate an asymmetric gradient force. For instance, Cheong *et al.*[35] used a cylindrical lens to create a line optical tweezer; by tilting the cylindrical lens in an off-axis manner, the intensity profile of LOT decreased monotonically along the longitudinal axis (Fig. 1c). Ma *et al.*[83] used a "Y" shape configuration of dual-channel LOT (Fig. 1d) to transport and sort particles of different sizes. By adjusting the relative power of the two LOT lines, one can make the transverse trapping force from the channel with higher laser power stronger than that from the channel with lower laser power for big particles but weaker for smaller particles, as the magnitude of optical force depends on both laser power and particle size. This strategy can be directly used in separating biological materials of interest. For example, Ma *et al.*[83] used LOT, assisted by Stokes drag in the fluid flow, to optically separate cells of different sizes.

While size-based separation using LOT has been explored to some extent, shape-based and mechanics-based separation[60] is another area seemingly wide open to be explored. Examples include shape-based separation of synthetic microparticles or shaped-based separation of blood components such as red blood cells and platelets. Particles with different shapes scatter light differently. Such phenomena have already been widely used in the fluorescence-activated cell sorting (FACS) instrument,[84] in which light scattering and fluorescence characteristics of each cell passing through the light are measured. Based on these measurements, cell separation is achieved by making use of electrical charge. This method, however, has limitations such as the need for labelling with antibodies for fluorescence detection and subsequent electrically induced damage to the cell during the cell separation phase. A dual- or multi-channel LOT could potentially be used without the need for cell labelling to separate cells of different shapes and mechanics.

Optical thermal ratchets (Brownian motors)

A model of a biological and artificial nanomachine is a thermal ratchet, a specific type of Brownian motor that uses a time-dependent asymmetric sawtooth potential to help produce directed diffusion along a line.[40,85,86] An optical trap, which is quickly moving along a line[86] or a circle,[41] allows the particle to diffuse freely in one dimension while confined in other dimensions. Then, temporal modulation of the spatial intensity profile can be used to induce a net drift and hence, creates an optical thermal ratchet,[41] as shown in Fig. 1(e and f). These models can be used in studying mechanisms for nanoscale motion.

Self-propelled cyclic motion

An example of a micromachine is Janus particles positioned inside non-scanning LOT. These particles in LOT are capable of self-propelled cyclic round-trip motion without external energy for active manipulation.[34] Janus particles, which show two distinct physical or chemical properties, can be designed to convert light energy to propulsion force. Liu *et al.*[34] used 5 μm-diameter polystyrene microspheres half-coated with gold film inside a static LOT. They found that the forces acting on a Janus particle strongly depend on its location and orientation along the longitudinal axis of the trap. The particle undergoes both translational and rotational motion in space and time, due to the asymmetric geometry and electromagnetic properties of the Janus particle. As a collective action of optical force and torque, Liu *et al.*[34] observed self-propelled cyclic motion of Janus particles inside LOT (Fig. 1g).

Inspired by the self-propelled motion of Janus particles and by incorporating microfluidic technologies in the LOT system, LOT opens up a wide range of possibilities in life science areas, ranging from medical diagnostics to drug delivery. The self-propulsion capability of these particles provides efficient fluid mixing, which is essential for efficiently probing the media and accelerating chemical detections. For instance, Jurado-Sanchez *et al.*[87] used both magnetically and chemically propelled Janus particles encapsulating reagents to detect bacterial endotoxin. The self-propulsion capability of these microparticles induces continuous fluid mixing, which is essential for detection efficiency. A Janus particle with cyclic motion enabled by LOT could provide controlled autonomous navigation through the medium. A Janus particle with such controlled motion could very well serve as a drug carrier. For instance, by implementing a proper microfluidic design, a Janus particle could capture the drug in one channel and move over to the other channel in a controlled way to deliver it. Alternatively, if there are various microfluidic channels along the line and the media in each channel is modified with pH or heat-sensitive molecules, the differential release of differential drugs from a Janus particle could be separately controlled in each channel.

Janus particles have also been introduced as a compatibilizer to make a better-blended and more stable polymer mixtures. Janus particles can effectively decrease average domain size in phase separation and induce local microphase separation during the early stages of phase separation in a polymer blend.[88] Utilizing LOT to controllably arrange and move the Janus particles within the blend has implications for the design of functional materials and enhancing performance of the material (*e.g.* photovoltaic performance) by optimizing the morphology of the phase-separated structure.

Summary

We have presented a brief overview of fundamentals and applications of line optical tweezers. The focus has been on transporting, funnelling, and rotating microspheres by trapping them along the longitudinal optical axis of a line optical trap. We have proposed future directions that can extend the applications of these controllable micromachines in various areas of soft matter, biological materials, and colloidal physics.

Conflicts of interest

There are no conflicts to declare.

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