

Drag-and-drop system manipulates microparticles in 3D

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A real-time 3D laser-manipulation system can be used to assemble, organize, and actuate particles, microtools, and living cells.

Over the past fifteen years, lasers have proven efficient and versatile at manipulating objects ranging in size from tens of nanometers to hundreds of micrometers. Until a few years ago, virtually all light-manipulation was based on the optical tweezers technique, in which particles trapped in a single strongly-focused laser beam were moved by translating the laser focus. At the beginning of the 21st century, researchers realized that much more versatile and general manipulation of molecules and particles was possible using specially-tailored 3D crystal-like structures of light. This sculpted light has unprecedented potential for manipulating mesoscopic objects. It has already been successfully used to organize small particles, including microbial cells, into patterns and to sort samples of particles according to their size.^{1,2}

Three-dimensional light structures can be created by modulating the spatial phase and polarization of laser light. A particularly promising technique is the generalized phase contrast (GPC) method invented and patented by our group at Risø National Laboratory.³ Based on a combination of programmable spatial light modulators and an advanced graphical user interface, the GPC method enables real-time, interactive, and arbitrary control over the dynamics and geometry of synthesized light patterns. Recent GPC-driven micro-manipulation experiments have shown that the method can provide fully user-guided assembly of many particles in a plane, control of particle stacking along the beam axis, manipulation of multiple hollow beads, and the organization of living cells into 3D colloidal structures. These demonstrations illustrate that the technique can be used not only for the improved synthesis of functional microstructures but also for actuating micro-scale tools: the noncontact method can provide the parallel actuation crucial for sophisticated opto- and micro-fluidic-based lab-on-a-chip systems.

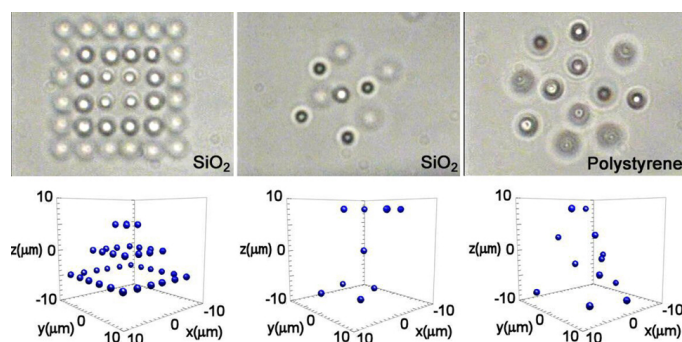


Figure 1. Silica (SiO_2) and polystyrene microparticles are trapped and moved into arbitrary constellations of colloidal structures using the generalized phase contrast (GPC) method. The bottom row shows the 3D locations of microparticles in the top row.

Because the GPC-synthesized beam traps have a large dynamic range for axial positioning of particles, the particles can be moved well outside the focal plane of a microscope objective lens. A particle out of focus becomes hard to see and measurements of particle position and velocity become unattainable. The GPC system, however, allows a user to observe the particles in an orthogonal plane. One can also specify the number and the individual properties of optical traps, including their transverse positions and the relative strengths of the opposing beams. Our experiments show that these degrees of control allow one to maneuver simultaneously trapped particles independently in three dimensions in real-time.^{4,5}

The versatility of the GPC approach opens the door for a range of new applications within biotechnology, materials research, and both micro- and nano-scale technology. One obvious application is to implement an all-optical lab-on-a-chip for non-invasive investigation of growth behavior in large cell colonies. The technology can be used to maintain natural growth condi-

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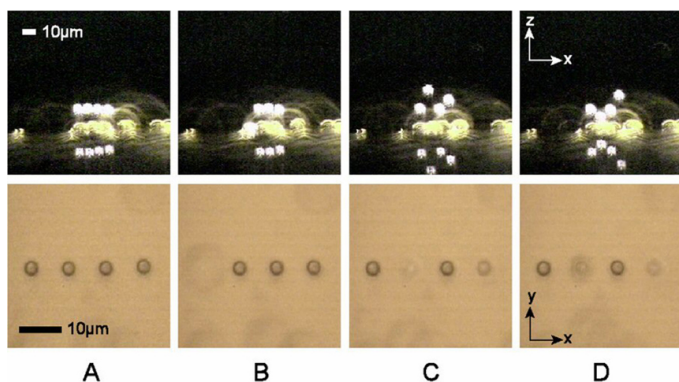


Figure 2. Laser beams manipulate polystyrene beads. The top and bottom rows show orthogonal views. (A): Micron-sized beads are optically levitated $15\mu\text{m}$ above a glass surface. The reflection of the beads in the glass surface can be seen due to the slightly angled side view. (B)-(D): A user controls the relative z-positions of the beads, showing $\sim 30\mu\text{m}$ axial dynamic range. The x-y viewing system is set to sharply image the plane $15\mu\text{m}$ above the bottom surface.

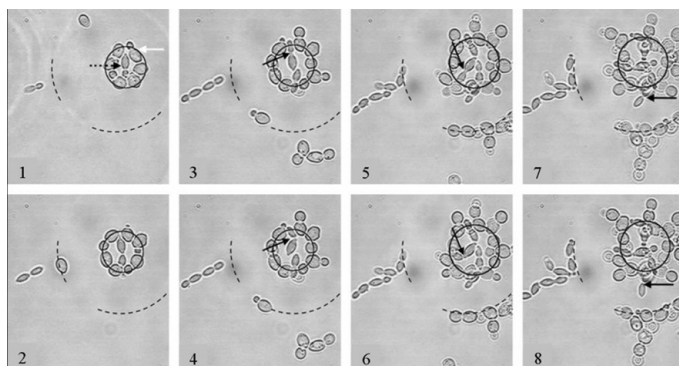


Figure 3. A micro-scale view of mixed-culture fermentation of different yeast cell types (*Hanseniaspora uvarum* and *Saccharomyces cerevisiae*) demonstrates non-invasive optical manipulation of living and dividing cell cultures over a long period.

tions by using sculpted laser light in the near-infrared. Figures 1 and 2 illustrate some of the possibilities of the GPC-system for experiments involving patterned or dynamically driven systems of colloidal particles.

These colloidal arrays might be used as analogs to systems that cannot be studied directly. For microbiologists, this technology serves as a non-invasive tool for manipulating cells into spatial configurations that may trigger variations in developmental features. By characterizing biophysical interaction phenomena, including confinement stress, in micro-organisms, microbiologists can better understand microbial cell-growth regulation in bio-films in medical, environmental, or industrial

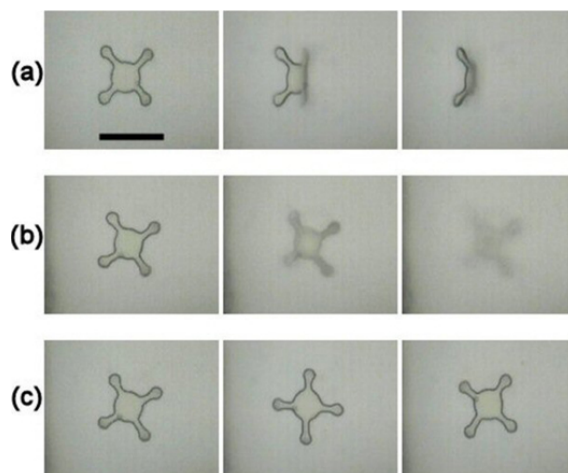


Figure 4. Multiple optical beams control the movement of a microstructure. (a) The structure is turned approximately 80° , which allows us to see the structure's flatness. The bar is $20\mu\text{m}$ long. (b) The structure is moved along the viewing axis. (c) The structure is rotated about a normal axis through its center.

settings, or, for another example, pro-biotic and pathogenic communities in the gastrointestinal tract. Using the GPC platform, researchers can investigate the phenomenon of confinement stress in bacteria, yeasts, and molds. Moreover, where confinement stress does play a role in microbial cell-growth regulation, the physiological mechanisms underlying this phenomenon can be studied. The interactive GPC system offers a unique tool for studying confinement stress in micro-organisms,⁶ because it allows for the arrangement of several particular cells at well-defined 3D distances from each other at well-defined moments of time (see Figure 3).

In another application, the GPC system has been used to interactively power and actuate specially fabricated and shaped glass structures with micrometer dimensions and submicron features. Functionally-shaped micro- and nano-fabricated structures, and their manipulation by multiple optical traps, have potentially exciting biophysical applications.⁷ An experimental example is shown in Figure 4.

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