An optical trapped microhand for manipulating micron-sized objects

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Abstract: We have developed a real time interface for holographic optical tweezers where the operator's fingertips are mapped to the positions of silica beads captured in optical traps. The beads act as the fingertips of a microhand which can be used to manipulate objects that otherwise do not lend themselves to tweezers control, e.g. objects that are strongly scattering or highly light sensitive. We illustrate the use of the microhand for the real time manipulation of micron sized chrome particles.

OCIS codes: (090.1970) Diffractive optics; (140.7010) Trapping; (230.6120) Spatial light modulators

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#76053 - $15.00 USD Received 13 October 2006; revised 15 November 2006; accepted 17 November 2006

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1. Introduction

Optical tweezers [1] have been revolutionised by the incorporation of spatial light modulators to split the laser beam into many individual traps that can be independently positioned; a technique called holographic optical tweezers [2]. Here we report on an interface using the operator's fingers to simultaneously determine the position and motion of several optical traps. In effect we use the beads captured in optical traps as the fingertips of a manipulating microhand. One traditional limitation of optical tweezers is their reliance on the gradient-force generated by the interaction of transparent objects with the focused laser light. Consequently, the trapping of opaque particles has remained problematic. Circumventing that fundamental problem, the present dynamic holographic system is demonstrated to use the digits of the microhand to accurately manipulate micron-sized metallic objects, expanding the range of particles that can be manipulated.

When placed in the tight focus of a laser beam, a micron-sized object is subject to a gradient-force and a light scattering force, both adding to gravity and forces associated with Brownian motion. For dielectric (i.e. transparent) particles the gradient force can correspond to a substantial fraction of the optical momentum, dominating over all other forces to create an optical trap centred on the beam focus.

For positioning a single optical trap, it is normal to place a beam steering mirror in a Fourier-plane of the trap itself, where an angular deviation of the collimated beam gives a lateral shift of the focused trap. This arrangement lends itself to replacement of the mirror with a diffractive optical element [3] that gives the additional freedom of introducing focal power and hence axial control of the trap position. One point of particular interest is the extremely high numerical aperture of the microscope systems typically employed. One important consequence is that two or more objects can be trapped at different heights along the microscope's optical axis, and then separated again [4]. Positioning the diffractive element in the Fourier plane of the trap means it is operating as a hologram, hence the term holographic optical tweezers. Using a spatial light modulator as the diffractive element allows the positioning of the traps at video frame-rates [5, 6]. Thus multiple optical traps can be controlled independently and simultaneously. Various algorithms have been employed for the design of the hologram allowing 3D arrangements of multiple traps, such as those used for creating complex 3D structures [7, 8] and performing simultaneously 3D optical manipulation and optical sectioning [9, 10]. In this latter work a 3D arrangement of beads was created in order to hold a biological sample indirectly. However, this 3D arrangement relied on a sequence of pre calculated holograms and therefore offered limited real time control.

For metallic particles between 10 and 100nm in diameter, the excitation of surface plasmons makes trapping at the beam focus possible [11]. However, for larger, micron-sized metallic particles, scattering forces dominate, repelling the particle from the beam. Although rapidly scanning a single beam around the particle [12] or using beams with annular intensity cross sections [13] allows trapping of metal particles, trapping of multiple particles at differing axial

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position can be problematic. Similarly, the direct trapping of biological samples such as cells can also be problematic. The cell can be damaged by intense illumination, or simply the low contrast in the refractive index between the cell and the surrounding fluid generates only very small trapping forces.

2. Hologram design

Whilst holographic optical tweezers offer much flexibility and control in the positioning of multiple traps, they can be computationally demanding. A simple and computationally efficient algorithm for hologram design relies upon the fact that a lateral displacement of a single trap requires a hologram corresponding to a blazed diffraction phase-grating with a period proportional to the displacement of the trap away from the beam axis. For an axial shift the hologram corresponds to a Fresnel lens. The modulo 2π addition of multiple holograms produces a hologram giving a single trap shifted from the original focus by the vectorial sum of the shifts produced by the individual holograms. Multiple traps are produced by the complex addition of the holograms defining individual traps. The magnitude of each input hologram corresponds to the individual trap strength and the argument of their sum gives the desired multi-trap hologram [14, 15]. The time-averaged contrast of the resulting traps can be maximized by introducing a random phase-shift between the individual holograms prior to their addition [16]. Although the optical resolution of the microscope system is 100's nm, the precision to which each of the beads can be positioned is better than 10nm [17], providing control at the nanoscale.

Within our application, we define the position of several traps of equal strength and map the $0-2\pi$ phase of the hologram onto an 8-bit grey-scale image, relayed onto the spatial light modulator via a video card interface. The 8-bit grey-scale lends itself to the use of inherently modulo 8-bit arithmetic. This computational efficiency means that a twin-processor, desktop computer can readily calculate and display 512x512 pixel holograms at 8 frames per second. This rate is sufficient for a real-time interface.

3. Experimental configuration

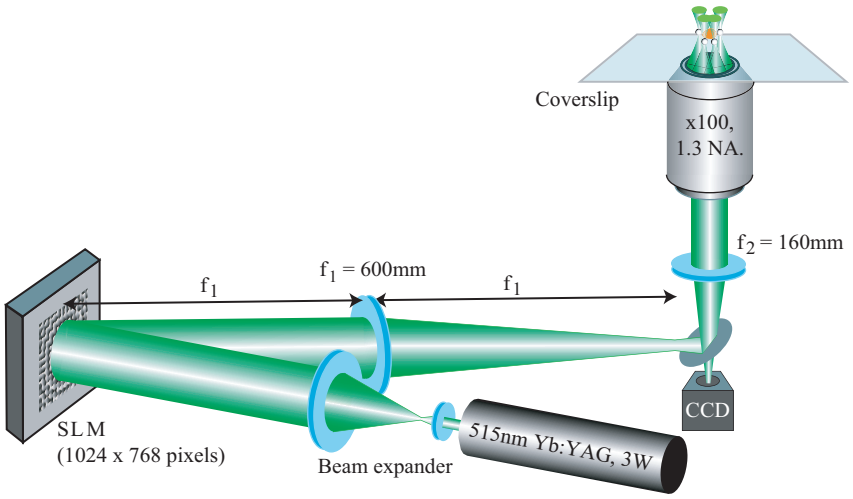

Fig. 1. The experimental configuration of the holographic optical tweezers. The plane of the SLM is positioned in the Fourier plane of the sample.

Our optical tweezers are configured around an inverted microscope with a 1.3NA, x100, Plan

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Neo-fluar objective, as illustrated in Fig. 1. The trapping laser is a diode-pumped, frequency-doubled solid-state laser emitting up to 3 watts of 515nm light that is expanded to fill the aperture of an electrically addressed spatial light modulator (Holoeye LC-R 2500), the plane of which is imaged onto the back aperture of the objective lens. The novelty of our system is that the trap locations are controlled by the positions of the operator's finger tips.

A single fire-wire interface camera positioned above the working area images the x and y positions of white beads attached to the fingers of a black glove, as illustrated in Fig.2. The z positions of the beads are unambiguously inferred from their apparent size in the image. These positions are scaled and fed to the hologram calculation algorithm to produce optical traps at the corresponding positions within the 3D space accessible to the holographic tweezers. The position of each fingertip is directly mapped to the position of each trapped bead within the tweezers. For trapping robustness and stability, the interface limits the maximum translation velocity of the traps ($< 5\mu$m/sec) so that too rapid a movement of the fingers results in a locking of the trap positions. This also allows a static arrangement of traps to be created by rapidly moving the fingers away from the camera, allowing further experiments on the trapped object without requiring the fingers to be held in place. To regain control on the traps, the fingers have to be re-positioned in coincidence with the locked traps (as shown in the first two frames of Fig. 4).

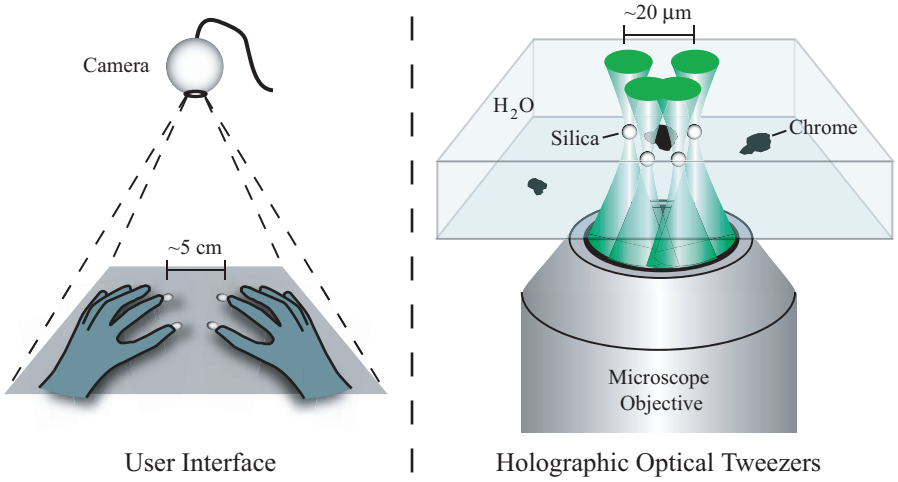

Fig. 2. A new approach to controlling optical tweezers. A single camera images the coordinates of white beads attached to fingertips. The position of each fingertip is mapped to the position of optical traps, providing a direct, visually controlled manipulation of microscale objects.

The selection of silica bead size is an important parameter in the operation of the microhand. Although the trapping beams are tightly focused, the comparatively high light intensity means that some light is still present around the edge of the beads. If the object to be manipulated is particularly sensitive to light or is highly scattering then this residual light may damage the object or expel it from the microhand. Whereas 2-micron diameter beads result in higher applied forces, 5-micron diameter beads better isolate the object from the trapping light. Optical tweezers typically can create a force of order 1pN per 1mW, meaning that the maximum force that can be exerted by the hand is limited by the power of the laser, and efficiency of the SLM and relay optics, to order of a few 100pN.

The holographic technique presented here allows for the fine control of multiple independent

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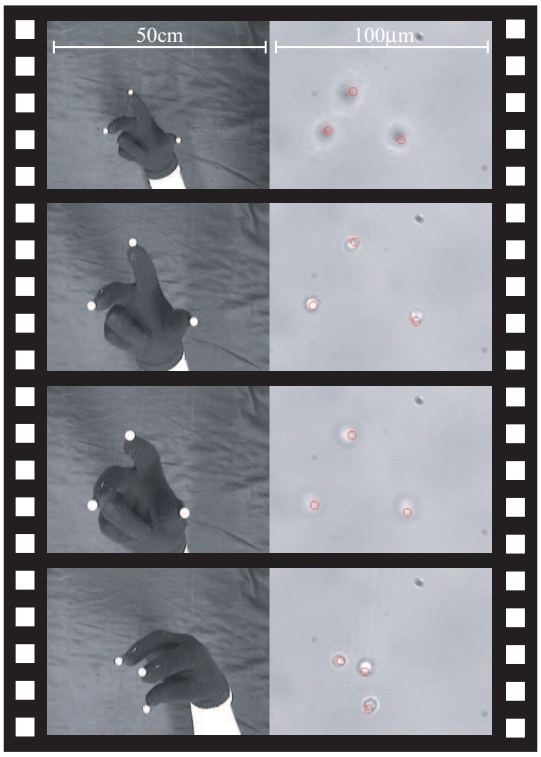

Fig. 3. Split screen video sequence showing control of the microhand in the lateral and axial directions. The axial position of each silica bead (5μm diameter) is determined by the size of it's corresponding white marker in the image. See accompanying movie, 3beads.avi (1.64MB).

traps, and provides the possibility for sophisticated interactions with micro- and nano-scale objects. In the present scheme, the operator's fingers can be adjusted to grasp and manipulate objects with complex geometries. Each of the beams acts as a digit of an optically controlled hand.

The spatial and temporal correspondence between fingertips and optical traps can be monitored by a split screen video (Fig. 3). Fingertips with white markers attached, can control the position and velocity of beads captured in the optical traps. In addition to controlling the lateral positions of the silica beads, determined by the lateral positions of the corresponding white markers, their axial positions are determined by the size of the white markers in the image.

We have demonstrated the microhand as a tool for manipulating micron sized chrome particles (Fig. 4). In this example, a chrome particle is selected and moved using four 100 mW power optical traps. In these conditions, the trapped five micron diameter beads can be independently translated at up to 5μm/s over a field of view approximately 80μm in diameter. The system conveniently enables grabbing, displacing, positioning, orientating, lifting and gentle releasing of irregular objects.

4. Discussion and conclusions

We believe that the microhand interface will make optical tweezers a more accessible tool within the multidisciplinary workplace. Removing the need to trap objects directly will greatly extend the range of applications to include both strongly scattering and highly light sensitive

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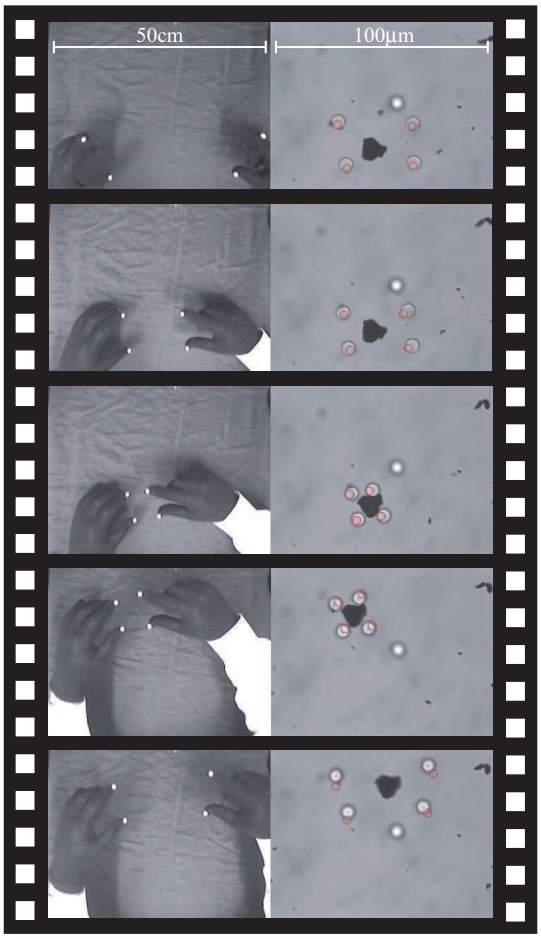

Fig. 4. Split screen video sequence of user interface and trapped beads (5μm diameter). Here, the microhand is used to select and move an irregularly shaped and opaque chrome particle. See accompanying movie, 4beads.avi (2.29MB).

objects. For example, multiple traps guided by the microhand interface could be put to use in cell sorting tasks requiring mechanically soft intervention with low light levels. The accurate and soft handling of cells, bacteria, or even subcellular organelles could be automated; enticingly, learning algorithms could acquire the operator's manual demonstration of the proper manipulative procedure, and generalize it to entire cell populations. More generally, the capacity of manipulating matter in three dimensions at the micro and nanoscale has great potential for future technologies in areas such as biomedicine and material research.

Acknowledgments

This work is supported by the RCUK.

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