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Optically controlled grippers for manipulating micron-sized particles

Graham Gibson, Louise Barron, Fiona Beck, Graeme Whyte and Miles Padgett

Physics and Astronomy, Kelvin Building, University of Glasgow,
Glasgow G12 8QQ, UK

E-mail: g.gibson@physics.gla.ac.uk

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Abstract. We report the development of a joystick controlled gripper for the real-time manipulation of micron-sized objects, driven using holographic optical tweezers (HOTs). The gripper consists of an arrangement of four silica beads, located in optical traps, which can be positioned and scaled in order to trap an object indirectly. The joystick can be used to grasp, move (lateral or axial), and change the orientation of the target object. The ability to trap objects indirectly allows us to demonstrate the manipulation of a strongly scattering micron-sized metallic particle.

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1. Introduction

Optical tweezers [1] have been implemented for many years. They use a high-magnification objective lens to focus a laser beam to produce a region of high electric field. The use of optical tweezers has traditionally been limited to manipulating transparent objects, where the gradient force dominates over all other forces to create an optical trap centred on the beam focus. However, trapping strongly scattering or highly light sensitive objects is more problematic. In the case of metallic particles the scattering force dominates, repelling the particle away from the beam focus. Authors have reported methods for successfully trapping metal particles indirectly [2, 3], but none offers precise control in the axial direction. An alternative method of optical manipulation using generalized phase contrast based counterpropagating light fields has been demonstrated and used to control microfabricated tools [4]. The direct trapping of cells is also problematic. The cell can be damaged by the high intensity of the trapping laser, particularly when the wavelength is not optimized, or the low contrast in refractive index between the cell and surrounding fluid generates only very small trapping forces.

Holographic optical tweezers (HOTs) [5] use a diffractive optical element, such as a programmable Spatial Light Modulator (SLM), to shape the light. HOTs have previously been used to create three dimensional (3D) arrangements of traps, such as those for creating complex 3D structures [6, 7] and performing simultaneously 3D optical manipulation and optical sectioning [8]. Using SLMs allows the creation of complex arrangements of optical traps which can be dynamically reconfigured at video frame-rates [9, 10]. The high numerical aperture of the microscope systems typically employed means that two or more trapped objects can be rotated about any axis of choice [11]. In this paper, we report a new approach where an arrangement of trapped objects, e.g., silica spheres, can be positioned and scaled, using a joystick control, to act as a tool for manipulating micron-sized metal particles (see figure 1).

2. Experimental configuration

2.1. Optical set-up

Our HOT system is configured around an inverted microscope (Zeiss Axiovert 200) with a 1.3NA, $\times 100$, Plan Neo-fluar objective. The trapping laser is a diode-pumped, frequency-doubled, solid-state laser emitting up to 3 watts of 515 nm light that is expanded to fill the aperture of an electrically addressed SLM (Holoeye LC-R 2500), the plane of which is imaged on to the back aperture of the objective lens.

2.2. Hologram design

We use a simple and computationally efficient algorithm for designing holograms which can produce single or multiple traps. The algorithm combines the phase holograms of basic optical elements: gratings which result in lateral shifts, and lenses which result in axial shifts. The modulo 2π addition of multiple holograms is used to create a single optical trap shifted from the original focus by the vector sum of the shifts produced by the individual holograms. The complex addition of multiple holograms is used to create multiple optical traps, each shifted from the original focus by the shift produced by each individual hologram. The magnitude of each input hologram corresponds to the individual trap strength and the argument of their sum gives

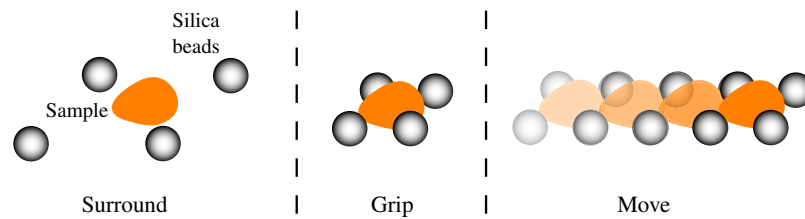


Figure 1. A new approach to controlling optical tweezers. An arrangement of silica beads located in optical traps can be positioned and scaled to act as a tool for manipulating micron-sized irregular objects.

the desired multi-trap hologram [12]. This algorithm has the advantage of being computationally efficient but can, for highly symmetrical trap arrangements, result in additional ‘ghost’ traps. We maximize the time-averaged contrast of our four trap pattern by introducing a random phase-shift between the individual holograms prior to their addition [13]. The precision to which multiple holographic optical traps can be positioned with a pixellated SLM is complicated, dependent not only on the number of pixels but their fill factor and other technical limitations [14, 15]. Some suggestions have been made that this may be better than 10 nm [16].

The joystick control is used to define the positions of four equi-strength traps where the $0-2\pi$ phase of the hologram is mapped on to an 8-bit grey-scale image, sent to the SLM via a video card interface. The 8-bit grey-scale lends itself to the use of inherently modulo 8-bit arithmetic which means that a twin-processor, desktop computer can readily calculate and display 512×512 pixel holograms at upwards of 10 frames per second; sufficient for a real-time interface.

2.3. User interface

We have previously developed software with a simple user-friendly interface that can be integrated within HOTs such that multiple optical traps can be created and individually controlled using a computer mouse or joystick [17]. Here, we use the joystick to control an arrangement of four optical traps. We trap four $5 \mu\text{m}$ diameter silica beads at the corners of a slightly out-of-plane square, each bead acting as a digit of an optically controlled hand, see figure 2. When largely spaced, the beads can be positioned to surround the target object. The square can then be scaled to confine the object between the trapped beads, translated to move or lift the object or rotated.

The lateral position is defined by the integral of joystick displacement, rotational position is the integral of joystick twist and axial spacing is controlled from the joystick toggle buttons. The selection of bead size is an important parameter in the operation of the gripper. Although the trapping beams are tightly focused, the comparatively high light intensity means that some light may still be present around the edge of the beads, especially when the beads are small. This can be problematic if the object is particularly sensitive to light, or is highly scattering, since the residual light may damage or expel the object from the gripper. In our tweezers’ configuration the size of the tightly focused laser spot is of order $0.5 \mu\text{m}$. We have found that $5 \mu\text{m}$ diameter beads adequately isolate the target object from the trapping light.

The hologram calculation runs at ~ 10 holograms per second allowing the user to manipulate trapped objects in real time. For robustness, the interface limits the maximum translation speed of the traps to $2-3 \mu\text{m}$ per second, ensuring that the object is not lost from the grip.



Figure 2. User interface for controlling optical tweezers. A joystick determines the position of a 3D arrangement of trapped silica beads which can be positioned around a target object. Toggle buttons on the joystick control the bead separation which is used to grip the target object. Twisting the joystick allows the target object to be rotated.

3. Results

To demonstrate the system, we used a sample containing a mixture of $5\ \mu\text{m}$ diameter silica beads and chrome particles in water. We recorded movies of the optical gripper being used to manipulate five-micron-sized chrome particles in real time. The joystick was used to position the four silica beads around a chrome particle, scaling the arrangement so as to grip the particle. Once gripped, the particle can be translated and rotated before being released at its new location (see figure 3). In this case, the best results were achieved by arranging the beads in a single plane.

We recorded movies while moving the chrome particle in the axial direction. This was achieved by gripping the particle as before then lowering/raising the microscope stage. In order to confine the particle in the axial direction, it was necessary to arrange the four silica beads at the corners of a slightly out of plane square, resulting in two of the beads appearing slightly out of focus in the video image (see figure 4). Once the particle has been lifted it can be translated before being lowered into its new location.

4. Conclusions

We have demonstrated a new approach to the interface and control of optical tweezers. The system relies upon the calculation of holograms to create multiple holographic traps which can be controlled in real time using a joystick interface. We have demonstrated that it is possible to grip, translate, rotate and lift micron-sized irregular metal particles that otherwise do not lend themselves to tweezers control. We believe that this technique can be extended to manipulate highly light sensitive objects such as cells, using beads coated in an appropriate anti-adhesive

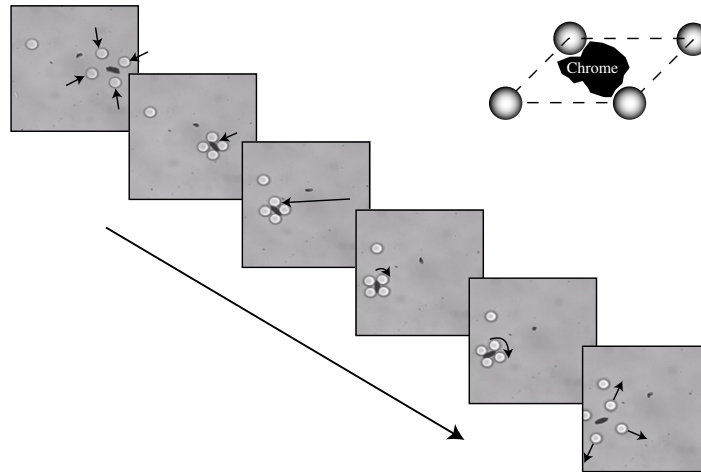


Figure 3. Video frame sequence of the optical gripper as it is positioned around a five-micron irregular chrome particle. Scaling the bead separation allows the chrome to be gripped, translated, rotated and released. See the accompanying [movie](#).

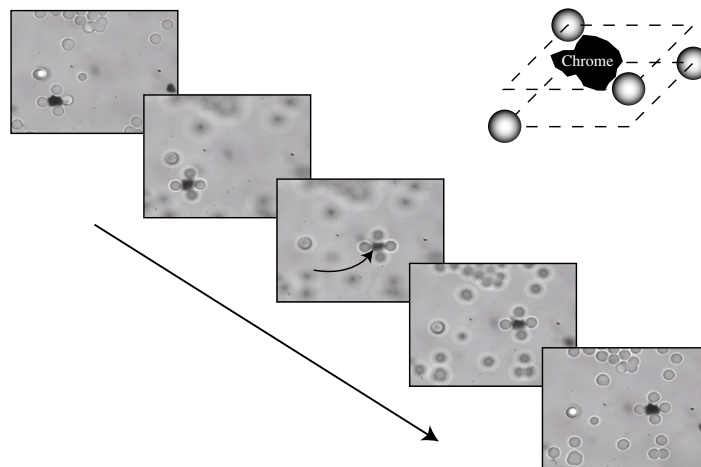


Figure 4. Video frame sequence of gripping a chrome particle as the microscope stage is lowered/raised. The chrome particle remains gripped while the stage is lowered causing the surrounding silica beads to move out of focus. The particle is then translated before raising the stage to bring the surrounding particles back into focus. See the accompanying [movie](#).

coating, making optical tweezers a more accessible tool within the multidisciplinary workplace. Removing the need to trap objects directly will further extend the range of applications in areas such as biomedicine and material research.

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