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Design of a simple, low-cost, computer-controlled, dual-beam optical tweezer system

C.J. Firby*, K.N. Smith, S.R. Gilroy, A. Porisky, A.Y. Elezzabi

Ultrafast Optics and Nanophotonics Laboratory, Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, T6G 1H9, Canada

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ABSTRACT

We present the design of a simple optical tweezer system. Our system modifies a simple compound microscope to provide one stationary and one steerable trap. Vertical integration of the optical components results in a device with a small footprint that is both compact and portable. Motorized mounting systems are constructed to achieve precise trap motion in three dimensions. Control and image acquisition are performed via an intuitive computer interface. Common and readily obtainable components were incorporated into the apparatus to reduce cost and complexity. The system was used to successfully trap and manipulate yeast cells, and by tuning the laser power, trapping can easily be extended to a wide range of biological and dielectric samples.

1. Introduction

Optical trapping is a phenomenon whereby small particles are held in place and manipulated by the radiation pressure of a focused laser beam. This effect has been demonstrated on particles ranging from atomic dimensions to tens of microns in size [1–4]. For large micron-sized objects, this can be qualitatively explained from a ray optics perspective. As light passes through a dielectric particle it will refract and change direction, corresponding to a net change in momentum of the photons; an equal and opposite momentum change for the particle must therefore be induced [1,2,4–7]. If the illuminating laser beam consists of a radially symmetric TEM_{00} mode, the intensity gradient acts to bring the particle back to the center of the beam [1,2,4–7]. Similarly, particles can be trapped in the axial dimension. When the particle is axially displaced from the beam's focal spot, the corresponding change in the refracted light will produce a force on the particle pushing it back toward the focal point [1,2,4–7]. This process is schematically depicted by Fig. 1(a)–(c).

The demonstration of particle trapping with radiation pressure in 1970 paved the way for the development of the first optical tweezers [8]. Since then, these devices have been invaluable tools for studying biological specimens, such as the motile properties of cells [9], and the mechanical properties of DNA and RNA, by providing a means of cell sorting and controlled force application [1,2,10–13]. The technology also has proven applications in laser cooling and many other areas of the physical sciences [1,3]. As such, a wide array of device implementations and methodologies have been developed in recent years.

The original optical tweezer designs involved focusing 515 nm light from an argon laser onto particles suspended in water, air, or a vacuum chamber [8,14]. Another approach involved the use of fiber optic probes to direct the light toward the sample [15]. The probes provide the advantage of spatially filtering the laser beam and removing aberrations from the beam profile. However, these systems are typically quite sensitive to vibrational disturbances and successful fiber trapping requires two laser beam-producing probes, one to hold the particle from each side [15].

In biological applications, it is often beneficial to trap more than one object. For example, the ends of a DNA molecule can be attached to small beads; the bead at one end of the DNA strand is anchored by an optical trap, and the other bead is pulled by a second trap, stretching the DNA and allowing a variety of measurements to be taken [11–13]. Alternatively, in cellular fusion, one cell can be trapped by a beam while another beam moves a second cell into contact with it, thus allowing them to be fused together by shorter wavelength laser pulses [16]. As such, various methods for achieving multi-object trapping have been developed. These range from simply implementing two separate laser beams into the device [7], to utilizing precise diffractive elements [17] or interference patterns [18] to create an array of traps. Multi-object trapping has also been accomplished by rapidly scanning a single laser beam between objects with the use of piezo-electronics, although this method requires intense computational power and expensive

* Corresponding author. Tel.: +1 7804922363.
E-mail address: firby@ualberta.ca (C.J. Firby).

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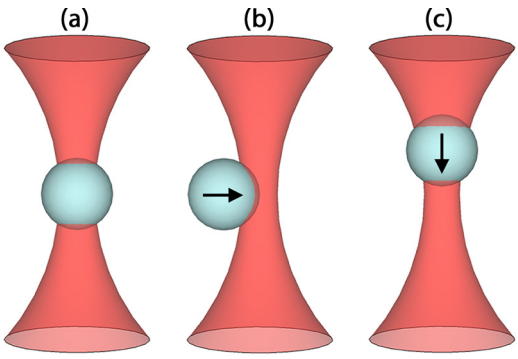

Fig. 1. Schematic illustration of the optical trapping process. (a) A particle is trapped at the beam's focal spot. (b) A particle radially displaced from the focal spot will experience a force directed toward the beam axis. (c) A particle axially displaced along the beam axis will experience a force toward the focal point. In both (b) and (c), the arrows indicate the direction of the force and the particle's motion.

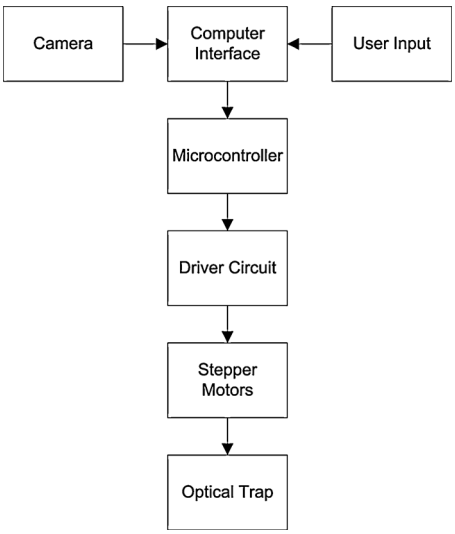

Fig. 2. Block diagram of the design. A camera feeds an image of the sample to the computer interface, which translates user input into serial commands. A microcontroller interprets these commands and relays the appropriate logic to a series of stepper motors via a current amplifying driver circuit to manipulate the laser beams, and hence the optical traps.

components and driver systems for the scanning [19]. The same effect is more commonly achieved via the use of acousto-optic modulators, which rapidly scan the beam between objects [10,20]. An even more elaborate method incorporates the use of plasmonic nanoantennas to hold an object in place [21].

Here, we present a simple design for a dual-beam optical tweezer system with one fully-steerable optical trap. The system was constructed around an extremely simple compound microscope and uses many components that are commonly found in the lab or can be easily purchased or fabricated. Optical components were coupled with stepper motors, and a graphical user interface was created to both control and automate the optical trap. A block diagram of the system flow is shown in Fig. 2.

2. Device design

2.1. Optics and optomechanical structure

Disadvantages of typical optical tweezer systems include a lack of portability and a large footprint. The structural elements of the device were built upon a metal plate bearing the same hole pattern as a standard optical breadboard, producing a portable device.

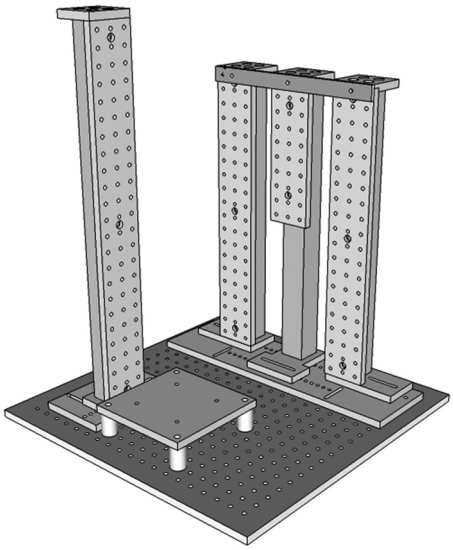

Fig. 3. The structural system used for the optical tweezer design. The microscope is situated on the central platform, with the imaging optics and camera on the tall plate to the left. Optics for manipulating the trapping laser beams are attached to the three adjustable plates in the back.

The centerpiece of the design was a simple compound microscope, which was fastened atop a small platform located in the middle. To reduce the footprint of the device and produce a compact system, the trapping and imaging optics were vertically integrated around the microscope. Four vertical supports were constructed from pieces of aluminum extrusion (part number 20.1033, Minitech Framing Systems LLC.) and a piece of optical breadboard was affixed to each for component mounting. Three plates were located behind the microscope platform for mounting the majority of the laser optics while one plate was situated to the side of the platform for the imaging optics. The structural system is shown in Fig. 3.

The device was designed around a Wild Heerbrugg M11-24085 microscope to demonstrate that an elaborate microscope is not required to build optical tweezers. This simple microscope acts as a convenient platform for combining both a sample stage and an objective lens. Note that it could be substituted for any low-cost compound microscope with these two components. In addition, one could even remove the microscope entirely and simply suspend an objective lens above a sample stage, however this platform is easier to work with. Slight modifications to the microscope were required though. The stationary stage was replaced with an x–y translational stage (CS-A512, OMAX) to provide sample movement, due to the fact that the default microscope stage provided no translational motion. Any high quality translational stage can be substituted for this part and provide comparable results. The incandescent lamp was replaced with a battery-powered LED light to increase portability and eliminate undesired sample heating. In addition, the standard objective lenses were replaced with a 100×, 1.25NA infinity corrected oil immersion objective (CA1079, American Optical), with a back aperture diameter of approximately 6 mm and an effective focal length of 1.8 mm. A high numerical aperture was required to produce a tight focal spot, and therefore create a strong optical trap, while the infinity corrected optics were required because the microscope itself does not contain an internal tube lens. Infinity corrected optics allow for the insertion of additional lenses at arbitrary locations, and hence greater control over the location of image formation. The eyepiece and top portion of the tube were removed as well, exposing the back aperture of the objective lens.