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Double-arm optical tweezer system for precise and dexterous handling of micro-objects in 3D workspace

Yoshio Tanaka

National Institute of Advanced Industrial Science and Technology (AIST), AIST Shikoku, 2217-14 Hayashi-cho, Takamatsu 761-0395, Japan

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A B S T R A C T

Double-arm manipulators are unfamiliar as equipment used in microscopic work in biomedical laboratories, whereas they are prevalent in factory automation and humanoids. For non-contact micromanipulation in three-dimensional (3D) workspaces, we propose and design a double-arm optical tweezer system that can easily exchange two types of end-effectors (i.e., optical landscapes for laser trapping) with a focus tunable lens and a microlens array. With a time-shared scanning approach under interactive personal computer (PC) mouse controls, the system can perform the precise and dexterous handling of micro-objects in a 3D workspace. As a proof of concept, we demonstrate the two-dimensional (2D) and 3D dexterous handling of microbeads in the motions of solving puzzle rings. We also demonstrate the precise and periodic patterning of microbeads for massive dynamic arrays. This double-arm system can be applied with versatile tools used for various non-contact micromanipulations in the biomedical field and for dynamic arrays in single cell and 3D biology.

1. Introduction

Double-arm manipulators are often employed in intracytoplasmic sperm injection (ICSI) procedures in medical biology, in which a glass needle attached to one arm is used to deliver sperm into an egg cell and a glass pipette attached to a second arm is used to hold the egg cell [1]. However, mechanical double-arm manipulators are unfamiliar as equipment used in microscopic work in biomedical laboratories, except ICSI, whereas they are prevalent in factory automation [2] and humanoids [3]. One reason for this is that micromanipulation with mechanical arms and hands causes inevitable physical contact with other objects, and these contacts lead to undesired adhesions between the end-effectors and objects because the adhesion force is dominant in a microscopic environment [4]; consequently, these adhesions prevent mechanical manipulators from performing precise or automated positioning tasks, such as the pickup-and-release of objects into desired positions, with a high efficiency. Conversely, optical tweezers—first demonstrated by Ashkin et al. [5] and extended to holographic [6], generalized phase contrast (GPC) [7], and time-shared scanning (TSS) tweezers [8] to trap multiple objects simultaneously—are well-established in non-contact micromanipulation techniques with high accuracy. Because the objective lens of a microscope used for optical tweezers functions as both a generator of manipulating forces and an observer of a workspace, optical tweezers combined with image processing techniques are particularly suitable for the automated and simultaneous micromanipulation of multiple objects [9–17]. Moreover, because one linear polarized beam emanated from a single laser source can be divided into two (i.e., p- and s-polarized) beams that never interfere with each other, double-arm (i.e., dual-trap) optical tweezers can be easily constructed without the introduction of an additional laser source [18–21] when compared with mechanical micromanipulators.

For various micromanipulation tasks in a true three-dimensional (3D) workspace, we propose and design a double-arm optical tweezer system that can easily exchange end-effectors (i.e., optical landscapes for laser trapping) with a focus tunable lens and a microlens array, which are inexpensive key optical components used to form various optical landscapes. With the TSS approach under interactive control by personal computer (PC) mice, this double-arm system can perform the precise and dexterous handling of micro-objects in a 3D workspace. As a proof of concept, we demonstrate the two-dimensional (2D) and the 3D dexterous handlings of multiple microbeads in the motions of solving puzzle rings. We also demonstrate the precise and periodic patterning of microbeads for massive dynamic arrays.

2. Double-arm optical tweezer system

For the manipulation of two spheres or the orientation control of a non-spherical object, dual-trap optical tweezers [18,19] have been developed using two divided (i.e., p- and s-polarized) beams since the early 1990s when multi-beam techniques including holograms, GPC, and TSS were not yet invented. However, if the intention is to manipulate a non-spherical object with six degrees of freedom (DOF), early dual-trap opti-

E-mail address: yo-tanaka@aist.go.jp

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cal tweezers do not have a sufficient control performance, and they must be extended to a 3D three-trap system by introducing an additional laser source [22]. Conversely, although 3D multi-trap optical tweezers using a single laser source have been demonstrated by multi-beam techniques (e.g., holograms [23] and counterpropagating-beam GPC [24]) since the middle 2000s, their achievements are still limited to the simple motions of trapped objects in a 3D workspace—the trajectories of trapped objects do not interfere with each other—and the 3D orientation control of an uncomplicated object. Here, to perform precise and dexterous handling of multiple micro-objects in the complex motions of solving puzzle rings, we design a double-arm optical tweezer system that can easily exchange two types of end-effectors (namely, optical landscapes for laser trapping). Compared with conventional multi-trap optical tweezers including our previous reported systems, the easy exchangeable end-effectors, which are the great advantage of this double-arm system, can generate the flexible and complex true 3D (or massive) optical traps based on TSS approach, without expensive spatial light modulators (SLMs).

Fig. 1 shows the optical and control system configurations of double-arm optical tweezers with replaceable optical elements including an electrical focus tunable lens (L_Z: Optotune EL-10-30-NIR-LD) for z-coordinate steering and a microlens array (L_A: Newport MALS14) for massive periodic patterning. This double-arm system is a multi-trap and two-beam optical tweezer in which two beams divided by a polarized beam splitter (PBS_1) individually configure the multi-trap optical tweezers (i.e., a true 3D-TSS with L_Z or periodic 2D with L_A) based on the TSS technique. These two types of TSS-based multi-trap optical tweezers that compose the double-arm system employ the same 2*f* relay optical system (not a 4*f* afocal relay system) under a common relay lens (L_R) used in the TSS part with a 2-axis scanning gimbal-mirror (GM_1 or GM_2). The detailed layouts for these two types of TSS tweezers based on the 2*f* relay system are illustrated in Fig. 1(b) and (c). Although 4*f* afocal relay systems are often employed in holographic or GPC optical tweezers that need an SLM, optical tweezers based on the 2*f* relay systems require a fewer number of optical elements resulting in an improved light transmission, less potential optical aberrations, and a simpler alignment. Moreover, for the replacement of end-effectors with a reduced cost, we can also design these 2*f* systems to use the same beam shaping lens (L_1) that directs a converging beam (or beamlets) through the GM_1 to a focus at a distance f_R prior to the relay lens (L_R), resulting in a collimated beam (or beamlets) incident on the objective lens (L_O). The desired focal length (f_Z) of L_Z and the optimal distance (d_{A1}) between L_A and L_1, which satisfy the necessary conditions for generating invariant trapping powers for all traps in a 3D workspace [25] and the objective imaging plane that equals the origin of the traps in the z-coordinate, are derived from the Gaussian lens equation [21,25,26] as follows:

$$f_z = \frac{f_1 f_R}{f_1 + f_R}, \tag{1}$$

$$d_{A1} = \frac{f_1^2}{f_R} + f_A + f_1, \tag{2}$$

where f_1, f_R, and f_A are the focal lengths of L_1, L_R, and L_A, respectively. In the case of our design ($f_1 = 120$ mm, $f_R = 170$ mm), the calculated f_z is 70.3 mm, which is almost centered in the tunable focal range. Thus, we can easily exchange the two types of end-effectors for the double-arm system by adjusting the position of L_1 to the designed distance (i.e., $2f_1$ or f_1) and by the replacement of an optical element (i.e., L_Z or L_A) equipped with a simple alignment mechanism.

3. Demonstrations

3.1. Two 3D optical hands

In this section, to demonstrate the advanced performance against conventional dual-trap and 3D multi-trap optical tweezers with an SLM, we select two true 3D-TSS optical tweezers for the abovementioned double-arm system. Here, we demonstrate the 2D and 3D dexterous handlings of microbeads (Duke Scientific, borosilicate glass microsphere, 2.5 μm) that dynamically form one set of puzzle rings by two true 3D-TSS multi-trap optical tweezers (i.e., two 3D optical hands). Namely, we interactively manipulate two puzzle rings by two PC mice, in the sequential motions of solving puzzle rings, while the individual microbeads forming each puzzle ring maintain their relative distances to each other. For each 3D-TSS hand, we adjusted the laser power at the entrance aperture of the objective lens to the equivalent value (50 mW) and set the dwell time of TSS between 12 ms and 15 ms.

Fig. 2 shows the video frame sequence of the 2D dexterous handling of microbeads, where the 24 microbeads indicated by colored circles dynamically form and maintain two question mark-shaped (‘?’-shaped) clusters (i.e., one set of ‘?’-shaped puzzle rings) in optical landscapes generated by two true 3D-TSS optical tweezers. First, the initial loading procedure for generating two ‘?’-shaped clusters of microbeads was performed under a similar algorithm to that in our previous paper used for dynamical microbead arrays [13]. The recognition algorithm based on the circular Hough transform and the collisionless path planning algorithm were executed to automatically gather microbeads up to the 12th nearest neighborhood of each origin ($O_{L/R}$) and to form two ‘?’-shaped clusters (as shown in Fig. 2(a)–(c)). Second, under bimanual control using two PC mice, these ‘?’-shaped clusters indicated by white and yellow circles were able to independently rotate around each origin in which one microbead indicated by a red circle was trapped. Each origin was also able to move toward an arbitrary position using the drag motion of a PC mouse; therefore, two ‘?’-shaped clusters were able to interactively manipulate to gradually link up with each other at their clasper parts (Fig. 2(c)–(f)), while the individual microbeads forming one set of puzzle rings maintain ‘?’ shapes. Finally, the two clusters that were entwined with each other were manipulated again to unbind their claspers, while they were rotated around each origin (Fig. 2(f)–(h)). Thus, we can interactively perform the 2D dexterous handling of two micro-objects that are trapped by two optical hands (i.e., optical multiple-force clamps [27]) using two PC mice.

In another demonstration shown in Fig. 3, fourteen microbeads forming one set of puzzle rings (i.e., two broken-octagons) are dexterously manipulated for entwining and disentwining with themselves in a 2D and 3D workspace. Fig. 3(a) shows a video frame sequence for the interactive crossing of the two broken-octagons in the same z-coordinates and their morphing into a 3D workspace, in which the red and green circles indicate the microbeads that form the two broken-octagons that are controlled by the left-handed and right-handed mice, respectively. After the interactive rotation and translation of the right broken-octagon (Fig. 3(a1) and (a2)), the two broken-octagons separating from each other were entwined in the same z-coordinates (Fig. 3(a3)). Subsequently, these entwined broken-octagons in the same z-coordinates were morphed into a 3D workspace by z-coordinate control (Fig. 3(a4)), while maintaining their xy-coordinates before and after the morphing. The 3D rendered views of the relative positions of the microbeads for this morphing are illustrated in Fig. 3 (ca3) and (ca4).

Fig. 3(b) shows the 2nd video frame sequence for the interactive crossing of the two broken-octagons that are initially trapped in a 3D workspace. First, the two broken-octagons separating from each other in the Cartesian coordinate system (as illustrated in Fig. 3(cb1)) were bimanually controlled to approach each other while facing their broken parts (Fig. 3(b1)). Subsequently, in Fig. 3(b2)–(b4), the 3D broken-octagon indicated by green circles was interactively entwined with another broken-octagon indicated by red circles while revolving on its own z-axis. The 3D rendered views of the relative positions of the microbeads for this entwining are illustrated in Fig. 3(cb2)–(cb4). Thus, we can perform the 3D dexterous handling of two micro-objects by the TSS approach combined with 3D interactive pointing and control devices (i.e., two PC mice).