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Grasping and manipulation of a micro-particle using multiple optical traps[☆]

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ABSTRACT

In existing control techniques for optical tweezers, a target particle is directly trapped and manipulated by a single laser beam. However, a typical force generated by an optical trap is extremely small (on the order of piconewtons) and thus it is not sufficient to manipulate a large cell or object. Besides, the feasibility of optical manipulation also depends on the physical properties of the specimen. An opaque object or object with the same refractive index as the fluid media may not be trapped directly by the laser beam. Therefore, current control techniques for optical tweezers cannot be utilized to manipulate various types of cells or objects, including untrappable or large ones. In this paper, robotic control techniques are developed for optical tweezers to achieve grasping and manipulation of a microscopic particle, which is beyond the capability of a single optical trap. First, multiple laser beams are generated, and each laser beam is utilized to trap and drive one grasping particle to form a desired shape around the target particle. A grasping formation of trapped particles is thus generated to hold the target particle. Then the target particle is manipulated to a desired position by controlling the motorized stage. The proposed control strategy is particularly suitable for manipulation of large particles, or even untrappable cells or objects. Rigorous mathematical formulations have been developed to analyze the control system for grasping and manipulation of the microscopic particle. Experimental results are presented to illustrate the performance of the proposed grasping and manipulation techniques.

1. Introduction

Micromanipulation is currently of increasing interest due to its wide range of applications in biology science and micro-system technology. Techniques that have been utilized for micromanipulation include atomic force microscopy (Kreplak, Wang, Aebi, & Kong, 2007), mechanical micromanipulator (Kasaya, Miyazaki, Saito, & Sato, 1999; Zhang, Chen, Liu, & Sun, 2010), magnetic tweezers (Pawashe, Floyd, & Sitti, 2009; Zhang, Huang, & Menq, 2010), electromagnetic tweezers (Yesin, Vollmers, & Nelson, 2006), and optical tweezers (Curtis, Koss, & Grier, 2002). Among these techniques, optical tweezers have received considerable attention because of its ability to manipulate microscopic objects precisely using highly focused laser beams.

The pioneer work in this field was conducted by Ashkin (1970) in the early 1970s. It was then demonstrated that a focused laser beam is able to tweeze and manipulate various types of objects such as dielectric micro-particles, viruses, bacteria, atoms, and molecules (Ashkin, 2000; Ashkin, Dziedzic, Bjorkholm, & Chu, 1986). Optical tweezers have been frequently utilized for manipulation of biological cells in recent years. Applications include cell separation (Murata et al., 2009), study of structure and mechanical properties of DNA (Rusu et al., 2001), and analysis of human red blood cells (Tan, Sun, Wang, & Huang, 2010).

In many applications, it is required to generate and manipulate multiple traps simultaneously. Techniques that have been developed to generate multiple traps include acousto-optic deflectors (AODs) (Vermeulena et al., 2006), laser scanning method (Arai, Yoshikawa, Sakami, & Fukuda, 2004; Visscher, Brakenhoff, & Kroll, 1993), and holographic optical tweezers (HOT) (Dufresne, Spalding, Dearing, Sheets, & Grier, 2001). The capability to generate and manipulate multiple traps independently at the same time has contributed extensively to the popularity of optical tweezing.

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Hence it has been utilized in many applications such as manipulation and assembling complex structures (Leach et al., 2004), multiple particle sorting (MacDonald, Spalding, & Dholakia, 2003), and indirect cell manipulation (Chowdhury, Svec, Wang, Losert, & Gupta, 2012; Chowdhury et al., 2014).

Demand for precise, efficient and reliable manipulation of optical trapping has led to the development of automatic manipulation methods. Several control techniques have been proposed to improve the efficiency and performance of micromanipulation. A simple control scheme developed for manipulation of microscopic objects was presented in Ibanez, Castanon, and Soriano (2011). Hu and Sun (2011) proposed a PID controller and a synchronization control technique for transportation of biological cells. Ranaweeraz and Bamieh (2005) discussed the performance of linear and nonlinear controllers for manipulation of spherical particles. An automated technique for trapping and manipulation of non-spherical objects based on computer vision techniques was presented in Tanaka, Kawada, Hirano, Ishikawa, and Kitajima (2008). Li and Cheah (2012) employed a dynamic region control technique to allow flexibility in optical manipulation tasks. The integrated trapping and control technique for cell manipulation with the consideration of both cell and manipulator dynamics for closed-loop control was developed in Li, Cheah, Hu, and Sun (2013). Yan, Cheah, Pham, and Slotine (2015) investigated the dynamic optical trapping problem of micro-particles under random perturbations and developed a controller with a velocity constraint based on the analysis. Besides, several control techniques have been proposed for automated manipulation of multiple particles. Chen and Sun (2012) utilized holographic optical tweezers to drive every pair of micro-particles into an assigned array. In Chen and Lou (2013), a flocking controller has been developed to move all trapped micro-particles into a desired region without collisions. Haghighi and Cheah (2015) proposed a control methodology for dynamic manipulation of multiple groups of cells.

As the typical trapping force of a laser beam is very small, the target particle may escape from the trap during the manipulation process. In order to assure the completion of the manipulation task, it is usually required to increase the trapping stiffness by increasing the laser power. However, the use of a high intensity laser beam to directly trap and manipulate the biological cell may cause photo-damage or even lead to the death of the cell. To avoid cell photo-damage, Chowdhury et al. (2014) proposed an indirect manipulation technique for cells using silica beads. The A* path planning algorithm was employed to generate a collision-free path for the system composed of the target cell and micro-beads. However, the work in Chowdhury et al. (2014) considered only the path planning problem while the dynamic interactions between the target cell and micro-beads, control law and stability analysis have not been taken into account for automated manipulation of cells.

In addition, optical trapping is also dependent on the physical properties of cells or objects. Current control techniques for optical tweezers cannot be utilized to manipulate various types of microscopic particles, such as large particles, laser-sensitive biological cells, or particles that cannot be trapped by the laser beam such as opaque objects. In this paper, robotic control techniques are proposed to achieve grasping and manipulation of a microscopic particle using multiple optical traps. Besides, rotation of particles, which cannot be performed by using a single optical trap, is also achieved. In this control strategy, multiple laser beams are first generated, and each laser beam is utilized to trap and automatically drive an identical trappable micro-particle to form a desired shape around the target particle. A grasping formation of trapped micro-particles is thus generated to hold the target particle. The target particle is then manipulated to a desired position by using the motorized stage. Finally, the

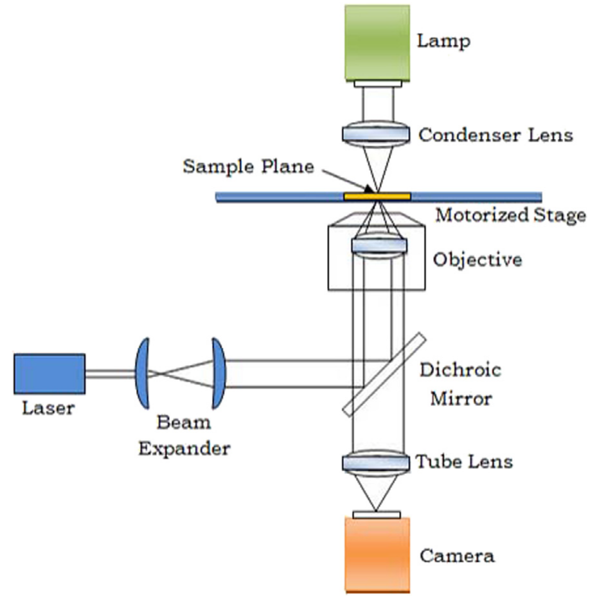

Fig. 1. A schematic of the optical tweezers system.

target particle can be released from the grasping formation. The manipulation control law is developed with the consideration of the dynamic interaction between the target particle and grasping particles. Moreover, the dynamics of the motorized stage is considered so that a complete control problem can be formulated and solved. The proposed control strategy is particularly desirable for manipulation of laser-sensitive biological cells, large particles, or even particles that are not trappable by optical tweezers. The main contribution of this paper is the formulation and solution of a robotic control problem to achieve a complete grasping and manipulation task in the micro-world, which is beyond the capability of single optical trapping. The stability of the system is analyzed by using Lyapunov-like analysis, and experimental results are presented to demonstrate the performance of the proposed controllers. A preliminary version of this paper was presented in Cheah, Ta, and Haghighi (2015). The result in Cheah et al. (2015) required a time-consuming manual operation to allocate and adjust the grasping particles around the target particle to hold it. This paper presents the extended version which includes a grasping technique to achieve a complete grasping and manipulation task of a microscopic particle. New experimental results on grasping and manipulation of the micro-particle are also presented.

2. Background on optical tweezers and problem statement

Optical tweezers are utilized to trap and manipulate microscopic objects using highly focused laser beams. When light travels through the microscale object, the transfer of momentum from photons to the object results in a trapping force that keeps the object near the center of the laser beam. A typical optical-tweezer system is shown in Fig. 1. The laser beam is expanded by a beam expander, reflected on dichroic mirror, then introduced into the inverted microscope to create a trap at the sample plane.

In order to achieve multiplexed optical tweezers, acousto-optic deflectors (AODs) are commonly used for generating multiple traps simultaneously. An acousto-optic deflector consists of a crystal whose refractive index is determined by variations of sound wave frequency. Hence, varying the frequency of the sound wave results in different deflection angles of the diffracted beam.

In this paper, robotic control techniques are developed to achieve grasping and manipulation of a microscopic particle,