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Stochastic control for optical manipulation of multiple microscopic objects[☆]

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ABSTRACT

While various control techniques have been developed for optical manipulation, the Brownian movement of microscopic objects in the medium is usually ignored for simplicity of analyzing the control systems. Nevertheless, due to the universality of the Brownian movement and its effect on optical manipulation of cells or micro-objects, it is required for the Brownian effect to be properly taken into consideration so as to ensure the stability and performance of the control systems. In this paper, we derive a stochastic control technique to achieve a theoretical framework for optical manipulation of multiple microscopic objects in the presence of the Brownian perturbations. In the proposed control methodology, a region control technique and a dynamic interaction approach are developed for collision-free manipulation of the target micro-objects with random perturbations. All the target micro-objects are trapped and manipulated simultaneously while being kept inside the desired dynamic region, and at the same time, preserving a minimum distance with each other to avoid collisions. While a bounded tracking or region error exists in current control techniques for optical manipulation due to the effect of the Brownian perturbations, this paper provides a new approach which guarantees that all the target micro-objects are kept inside the desired region during the course of manipulation. Rigorous mathematical formulation has been developed for automated manipulation of multiple microscopic objects in the presence of the Brownian perturbations, and experimental results are presented to demonstrate the feasibility and effectiveness of the proposed control technique.

1. Introduction

In the past few decades, numerous achievements in robotic and automation technologies have thoroughly revolutionized the modern manufacturing industries. Besides, increasing interests in nanotechnology and biological sciences have brought to the necessity of robotics and automation at micro and nano scales, thus opening up new challenges to understanding robotic manipulation of micro/nano-objects. The studies of micro and nano manipulations also bring up new research problems which diverge from the traditional robotic manipulation tasks.

Among the techniques utilized in micro-manipulation, optical tweezers are currently of increasing interest due to their capability of manipulating microscopic objects precisely without direct physical contact. In optical tweezers, various types of objects such as micro-particles, viruses, bacteria, atoms, and molecules are able to be trapped and manipulated by using highly focused laser beams (Ashkin, 2000; Ashkin, Dziedzic, Bjorkholm, & Chu, 1986). Numerous applications of optical trapping have been established recently, including in vitro fertilization (Iritani, 1991), cell transportation (Ashkin, Dziedzic, & Yamane, 1987), cell fusion (Ogle, Cascalho, & Platt, 2005), nuclear transplantation (Wilmut et al., 2002) and drug discovery (Drews, 2000).

In many applications, it is required to manipulate multiple optical traps at the same time. Various techniques have thus been utilized to allow multiple traps to be generated simultaneously, including holographic optical tweezers (HOT) (Dufresne, Spalding, Dearing, Sheets, & Grier, 2001), laser scanning method (Arai, Yoshikawa, Sakami, & Fukuda, 2004; Visscher, Brakenhoff, & Kroll, 1993), and acousto-optic deflectors (AODs) (Vermeulena et al., 2006). The ability to independently manipulate multiple traps at the same time has thus enhanced largely to the popularity of optical trapping. Various applications have been achieved so far, including indirect transportation of cell using gripper formation (Chowdhury et al., 2014), grasping and manipulation of cell (Cheah, Ta, & Haghighi, 2016), multiple particles sorting (MacDonald, Spalding, & Dholakia, 2003), manipulation and assembling

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complex structure (Leach et al., 2004), and study of cell–cell interactions (Gou, Han, Hu, Leung, & Sun, 2013).

Demand for accurate, efficient, and reliable optical tweezing of cells or microscopic objects has brought to the development of automatic manipulation approaches. Several automated techniques and control systems have been developed in order to meliorate the efficiency and performance of optical micro-manipulation. In Chowdhury et al. (2013) and Wu, Sun, Huang, and Xi (2013), motion planning and path planning algorithms were utilized for collision-free transportation of the target objects. Ibanez, Castanon, and Soriano (2011) developed a simple control methodology to achieve automated transportation of a micro-particle in a viscous medium. Hu and Sun (2011) introduced a synchronization control approach and derived a PID controller for manipulation of cell with the consideration of simplified cell dynamics. Wallin, Ojala, Haeggstrom, and Tuma (2008) developed real-time feedback control of a micro-particle's position to enhance the effective lateral trapping stiffness. Comparisons between the nonlinear and linear controllers for manipulation of a spherical micro-particle were discussed in Ranaweeraz and Bamieh (2005). Cheah, Ta, and Haghighi (2015) proposed a robotic control technique for automated cell manipulation by using several trapped particles to hold the cell, and robotic stage control to transport it to a desired location. Cohen and Moerner (2005) presented a control methodology for trapping and transportation of a single nanoscale object using fluorescence microscopy. A control framework for integrated trapping and manipulation of cell was presented in Li, Cheah, Hu, and Sun (2013), in which both cell and motorized stage dynamics were taken into consideration. Besides, several approaches have been introduced for automated manipulation of multiple cells or microscopic objects. Chen and Sun (2012) derived a control methodology to drive every pair of microscopic objects into a desired array with holographic optical tweezers. Ta and Cheah (2017) developed a robotic control technique for coordinative manipulation of multiple microscopic objects with arbitrary types in the micro-world by using laser-driven fingertips.

Though the effect of the Brownian motion is usually disregarded in existing control techniques for optical manipulation for the simplification of the control system analysis, this presumption is not always valid due to the effect of the Brownian perturbations on the precision and stability of the control systems. Since the effect becomes even more significant as the sizes of the objects decrease due to a faster diffusion rate, it is important to properly take into account the effect of the Brownian motion in the analysis so as to ensure the stability and performance of the micro-manipulation systems. Several techniques have been proposed for automated optical manipulation of micro-objects with the consideration of the Brownian perturbations. In Banerjee, Balijepalli, Gupta, and LeBrun (2009), a simplified trapping probability model was developed from simulation of the optical tweezers system with the consideration of the Brownian motion. Huang, Zhang, and Menq (2009) investigated a minimum variance control methodology for minimization of the Brownian effect on an optically trapped probe. A stochastic dynamic programming based motion planning framework for manipulation of a micro-particle was developed in Banerjee, Pomerance, Losert, and Gupta (2010). In this technique, the particle is allowed to be transported without collisions with randomly moving obstacles. Li, Yan, and Cheah (2016) developed a robotic control methodology for automated trapping and transportation of a micro-object with the Brownian effect. Yan, Cheah, Ta, and Pham (2016) proposed a controller with velocity constraint for manipulation of a micro-object in the presence of the Brownian motion.

However, existing manipulation techniques for optical manipulation of microscopic objects with the consideration of the Brownian motion are limited to a single object. In addition, a region or tracking error exists in the analysis of these control techniques due to the effect of the Brownian motion. Therefore, it is important for the Brownian effect to be considered properly so as to ensure the stability and performance of the optical manipulation systems. In this paper, a stochastic control technique is proposed to achieve automated collision-free manipulation of multiple micro-objects in the presence of the Brownian perturbations. All the target objects are first trapped by using the laser tweezers, and a desired dynamic region is generated to enfold all the target micro-objects. A region control technique and a dynamic interaction approach are then utilized for global manipulation of all the target objects while keeping them in the desired dynamic region, and concurrently, preserving a minimum distance between the target objects for collision avoidance. This paper provides a theoretical analysis for automated collision-free manipulation of multiple micro-objects in the presence of stochastic perturbations. While a bounded region or tracking error exists in current control techniques for optical tweezers due to the effect of the Brownian perturbations, this paper provides a new approach which guarantees that all the target micro-objects are kept inside the desired region during the course of manipulation. The dynamics of the target microscopic objects in the presence of the Brownian perturbations is considered, and experimental results are presented to demonstrate the effectiveness of the proposed control technique. A preliminary version of this paper was presented in Ta and Cheah (2016). In Ta and Cheah (2016), it is only guaranteed that all the target objects are kept inside the desired region during manipulation, but there is no guarantee on the collision-free movement of the target objects during the course of manipulation. In addition, a model-based control scheme has been presented for manipulation of multiple micro-objects with the Brownian perturbations, in which the dynamic model parameters are required to be known priori in the controller. This paper presents an extended version in which a new approach has been proposed to guarantee the collision-free movement of the microscopic objects, and at the same time, ensuring that all the target objects are kept inside the desired region during the course of manipulation, even in the presence of the Brownian perturbations. In addition, an adaptive control scheme is also included for collision-free manipulation of multiple micro-objects with Brownian perturbations and unknown dynamic model parameters. The detailed proof of the stability analysis and a new set of experiments are also provided in this version.

The remaining parts of this paper are organized as follows: Section 2 introduces the preliminary on optical trapping and dynamic equation. Section 3 is devoted to a region control approach for manipulation of multiple microscopic objects. Section 4 presents a dynamic interaction approach for collision-free movement of the target microscopic objects, followed by the development of controller in Section 5. Section 6 presents experimental results to illustrate the performance of the proposed control technique. Section 7 concludes the paper.

2. Preliminary on optical trapping and dynamic equation

In optical manipulation, highly focused laser beams are employed to tweeze and drive micro or nano-objects by exerting extremely small trapping forces on the objects. A schematic of an optical manipulation system is illustrated in Fig. 1. Several optical systems, including a beam expander, a dichroic mirror, and an objective lens are utilized to transfer a laser beam and then create a laser tweezer at the sample plane. Besides, camera and lightening systems are used for observation of the specimen.

In this paper, we propose a stochastic control technique for automated collision-free manipulation of multiple microscopic objects with Brownian perturbations. The Brownian movement, which is the random motion of micro or nano-objects in a fluid medium, is modeled as a stochastic process as follows (Morters & Peres, 2010):