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Cooperative and mobile manipulation of multiple microscopic objects based on micro-hands and laser-stage control ☆

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A R T I C L E I N F O

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While various techniques have been developed for manipulation of biological cells or micro-objects using optical tweezers, the performance and feasibility of these techniques are mostly dependent on the physical properties of the target objects to be manipulated. In these existing techniques, direct trapping and manipulation of the manipulated objects using laser traps are performed, and therefore, existing techniques for optical manipulation are not capable of coordinating and manipulating various types of objects in the micro-world, including untrappable micro-objects, relatively large micro-objects, and laser sensitive biological cells. In this paper, a cooperative control technique is proposed for coordinative and mobile manipulation of multiple microscopic objects using micro-hands with multiple laser-driven fingertips and robot-assisted stage control. Several virtual micro-hands are formed by coordinating multiple optically trapped micro-particles that serve as the laser-driven fingertips, and then utilized for individual and coordinative manipulation of the target micro-objects. Simultaneously, global transportation of all the grasped target objects is performed by controlling the robot-assisted stage. While it is difficult to design multi-fingered hands in micro-scale due to scaling effect, this paper presents the first result on cooperative and mobile manipulation of multiple micro-objects using multiple micro-hands with laser-driven fingertips and robot-assisted stage control. In this paper, a primary study on repositioning strategy of the laser-driven fingertips is also introduced to allow the fingertips in a grasping formation to be repositioned. Rigorous mathematical formulations and solutions are derived to achieve the control objective, and experimental results are presented to demonstrate the effectiveness of the proposed control technique.

1. Introduction

Human hands are capable of coordinating multiple fingers to grasp, rotate, and move various types of objects to perform an immense number of tasks or activities. In addition, the mobility of the whole body allows human to carry out tasks which are beyond the reach of hands. Though much progress has been obtained in understanding robotic manipulation using robotic systems in the physical world, it is still difficult to reproduce such maneuverability in the micro-world as the study of micro-manipulation opens up new research and technological issues which diverge from traditional robotic manipulation.

In the past few years, much effort has been dedicated to the research and development of micro-manipulation. The ability to manipulate biological cells or microscopic objects has contributed extensively to the research of biology science and clinical diagnosis. Numerous breakthroughs and applications have been achieved so far, including studies of cell fusion (Ogle, Cascalho, & Platt, 2005), drug discovery (Drews, 2000), cancer studies (Suresh, 2007), and analysis of human red blood cells (Tan, Sun, Wang, & Huang, 2010).

Various state-of-the-art techniques have been established in micro-manipulation, including magnetic tweezers (Pawashe, Floyd, & Sitti, 2009; Yesin, Exner, Vollmers, & Nelson, 2005), electrokinetic forces (Pethig, Talary, & Lee, 2003), hydrodynamic flows (Kessler, 1985), acoustic vibration (Chladni, 1787), and optical tweezers (Arai, Yoshikawa, Sakami, & Fukuda, 2004; Grier, 2003). Magnetic tweezers and other mechanisms (Chladni, 1787; Kessler, 1985; Pawashe et al., 2009; Pethig et al., 2003; Yesin et al., 2005) produce high throughput, but lack the spatial resolution or flexibility required for precise control of individual microscopic objects. Optical tweezers, on the other hand, is currently of increasing interest due to its capability of manipulating individual cells or micro-objects precisely and independently.

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In optical manipulation, it was first reported in early 1970s that a highly focused laser beam is capable of trapping and manipulation of various types of objects in the micro-world such as atoms, bacteria, and dielectric micro-particles (Ashkin, 1970). Since then, several robotic and automated techniques have been proposed for accurate and reliable manipulation of a single biological cell or microscopic object using optical tweezers. In Chowdhury, Svec, Wang, Losert, and Gupta (2012); Chowdhury et al. (2014); Wu, Sun, Huang, and Xi (2013), motion planning and path planning algorithms were employed for collision-free transportation of a target biological cell. A simple control scheme for manipulation of a microscopic particle was presented in Ibanez, Castanon, and Soriano (2011). Ranaweeraz and Bamieh (2005) discussed the performances of linear and nonlinear controllers in manipulation of a spherical micro-particle. In Hu and Sun (2011), a synchronization control technique and a PID controller was developed for transportation of a biological cell. Cheah, Li, Yan, and Sun (2014) developed a simple set-point controller for a trapped target cell, in which dynamic interactions between the laser trap and the target cell were taken into account. A grasping and manipulation technique for transportation of a microscopic object was proposed in Cheah, Ta, and Haghighi (2016). In Li, Cheah, Hu, and Sun (2013), an integrated trapping and manipulation technique was developed for transportation of a biological cell, in which the dynamics of both cell and robotic stage were taken into consideration. In Hayakawa, Kikukawa, Maruyama, and Arai (2016) and Ichikawa, Arai, Yoshikawa, Uchida, and Fukuda (2005), laser-driven gel micro-tools are utilized for indirect manipulation of a single cell by adhering the cell to the gel on the micro-tool. However, the gel must be mixed with the culture medium to be generated (Ichikawa et al., 2005), or the micro-tool needs to be fabricated beforehand (Hayakawa et al., 2016), and thus limiting feasible applications of the methods. The proposed techniques in Hayakawa et al. (2016) and Ichikawa et al. (2005) also depend on temperature control of the micro-tools, such that the cell-adhesion property of the gel can be used to adhere or release the cells from the micro-tool.

In the aforementioned approaches and control techniques, only one single cell or microscopic object is trapped and manipulated at a time. However, in the research and applications of biological sciences, including the study of cell–cell interactions, cell adhesion, cell fusion, and cell hybrids, etc., it is required that multiple cells are coordinatively manipulated at the same time. Besides, the ability to manipulate multiple cells or microscopic objects simultaneously also plays a significant role in providing a fast, productive, and high-throughput method for the research and applications of cell separation, cell sorting, and drug delivery. Several methodologies and techniques have thus been developed for automated and coordinative manipulation of multiple cells or microscopic objects. In Chen and Lou (2013) and Chen and Sun (2012), control techniques for transportation of multiple microscopic objects into a desired array and a desired region was developed respectively. Chapin, Germain, and Dufresne (2006) proposed an automated technique for trapping, assembly, and sorting of multiple micro-particles using holographic optical tweezers. In Villangca, Palima, Banas, and Gluckstad (2016), a light-driven micro-tool equipped with a syringe function has been fabricated and utilized for loading and unloading of small silica and polystyrene beads. Though the proposed method (Villangca et al., 2016) can be utilized for transportation of multiple beads at the same time, independent control of the micro-objects within the group cannot be achieved. A stochastic control technique for collision-free manipulation of multiple microscopic objects with the consideration of the Brownian perturbations was presented in Ta and Cheah (2016). Haghighi and Cheah (2016) developed a control methodology for robotic manipulation of multiple groups of microscopic objects.

While human hands are able to coordinate and manipulate multiple objects of any types easily and skilfully, it is difficult for current micro-manipulation techniques to reproduce such dexterity in the micro-world. Acoustic vibration (Zhou, Sariola, Latifi, & Liimatainen, 2016) is shown to be capable of individual manipulation of multiple micro-objects, but only with approximate movement of the target objects. In optical manipulation, the effectiveness and feasibility of current optical manipulation techniques for multiple micro-objects mostly depend on the physical properties of the target micro-objects to be manipulated. To be specific, these current techniques employ laser beams to directly trap and manipulate the target objects, and thus they cannot be utilized for trapping and coordinative manipulation of micro-objects with the same or very high refractive indexes. In addition, as the trapping force of each individual laser beam is extremely small, it is not sufficient to trap and manipulate cell or micro-object which is relatively large. Besides, the use of the laser tweezers for direct trapping and coordinative manipulation of biological cells may cause photo-damages or lead to death of the manipulated cells. Therefore, current control techniques for optical manipulation cannot be utilized for trapping and coordinative manipulation of multiple target objects with arbitrary types in the micro-world. To overcome this problem, a preliminary study was presented in Ta and Cheah (2017) by developing a robotic control technique for manipulation of multiple micro-objects using multiple laser-driven fingertips. However, the proposed technique in Ta and Cheah (2017) was only limited to local manipulation of the target micro-objects within the field of view of the camera.

Inspired by the competence of human which are able to coordinate and manipulate multiple objects effectively with the aid of hands together with the mobility of the whole body, this paper proposes a robotic control technique for optical manipulation of multiple microscopic objects by cooperative control of micro-hands with multiple fingertips and robot-assisted stage. In this control technique, multiple laser beams are first generated, and each laser beam is employed to trap a micro-particle such as a micro-bead. By coordinating the trapped micro-particles which serve as the laser-driven fingertips, several virtual micro-hands are thus formed to grasp the target micro-objects. Cooperative control of the multi-fingered micro-hands and the robot-assisted stage is then utilized for coordinative and simultaneous manipulation of the target micro-objects. In particular, individual and coordinative manipulation of the target micro-objects are performed by maneuvering the multi-fingered micro-hands, while robot-assisted stage, which is responsible for the mobility of the whole system, is utilized for global transportation of all the target objects to destinations which can be beyond the limited field of view of the camera. In this paper, a primary study in repositioning technique of the laser-driven fingertips is also introduced to allow the fingertips in a grasping formation to be repositioned. The control algorithm is developed with the consideration of the dynamic interactions between the target objects and the micro-hands as well as the dynamics of the robot-assisted stage. Besides, interactions between different micro-hands are also taken into account to ensure the collision-free movement of the control system during the course of manipulation. This paper provides a robotic control framework for optical manipulation of multiple micro-objects using robotic tweezers, which can even be applicable for coordination and simultaneous manipulation of objects that are not trappable by using laser traps, arbitrary large micro-objects, and laser-sensitive biological cells. Also, the proposed control technique can be utilized for independent, cooperative, and group manipulation of multiple micro-objects without the demand of specific types of the liquid medium or the fabricated micro-tools, and thus enhancing the feasible applications of optical manipulation. This is the first result on cooperative manipulation of multiple micro-objects with