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2018

Ta, Q. M., & Cheah, C. C. (2018). Cooperative and mobile manipulation of multiple microscopic objects based on micro-hands and laser-stage control. *Automatica*, 98201-214. doi:10.1016/j.automatica.2018.09.011

<https://hdl.handle.net/10356/81382>

<https://doi.org/10.1016/j.automatica.2018.09.011>

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Cooperative and Mobile Manipulation of Multiple Microscopic Objects based on Micro-hands and Laser-Stage Control

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Abstract

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.

Key words: micro-manipulation, cooperative manipulators, adaptive control, microsystems: nano- and micro-technologies, motion control

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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.

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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 [1], drug discovery [2], cancer studies [3], and analysis of human red blood cells [4].

Various state-of-the-art techniques have been established in micro-manipulation, including magnetic tweezers [5], [6], electrokinetic forces [7], hydrodynamic flows [8], acoustic vibration [9], and optical tweezers [10], [11]. Magnetic tweezers and other mechanisms [5]- [9] 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.

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 [12]. 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 [13]- [15], 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 [16]. Ranaweeraz *et al.* [17] discussed the performances of linear and non-linear controllers in manipulation of a spherical micro-particle. In [18], a synchronization control technique and a PID controller was developed for transportation of a biological cell. Cheah *et al.* [19] 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 [20]. In [21], 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 [22, 23], 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 [22], or the micro-tool needs to be fabricated beforehand [23], and thus limiting feasible applications of the methods. The proposed techniques in [22, 23] 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 [24] and [25], control techniques for transportation of multiple microscopic objects into a desired array and a desired region was developed respectively. Chapin *et al.* [26] proposed an automated technique for trapping, assembly, and sorting of multiple micro-particles using holographic optical tweezers. In [27], 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 [27] can be uti-

lized 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 [28]. Reza and Cheah [29] 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 [30] 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 [31] by developing a robotic control technique for manipulation of multiple micro-objects using multiple laser-driven fingertips. However, the proposed technique in [31] 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 arbitrary types using multiple micro-hands and robot-assisted stage control, and thus bring robotic micro-manipulation closer to robotic manipulators in the physical world. Rigorous mathematical formulation and stability analysis for cooperative manipulation of multiple micro-objects based on laser-stage coordination are derived, and experimental results are presented to demonstrate the effectiveness of the proposed control technique.

2 Problem Statements and Dynamic Equations

Optical tweezers are able to trap and manipulate microscopic objects by using highly focused laser beams. When the light travels through a microscopic object, the transfer of momentum from photons to the object results in a trapping force (typically on the order of piconewtons) that keeps the object near the center of the laser beam. Fig. 1 illustrates a typical optical tweezers system. A laser beam is first emitted from a laser source, expanded by a beam expander, then transferred by several steering optical systems to create a trap at the sample plane.

In optical manipulation of microscopic objects using robotic tweezers, the trapped target objects can be manipulated by either (i) moving the laser traps or (ii) moving the robot-assisted stage while fixing the laser traps. While manipulation of the target objects by moving the laser traps (i) is only limited within the field of view of the camera, robot-assisted stage control (ii) can

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

be utilized to manipulate the trapped target objects to any positions which are beyond the field of view of the camera, and thus enlarging the working space of optical tweezing.

In the studies of cell-cell interactions, cell fusion, cell hybrids, and many other biological applications, it is required that multiple target cells or microscopic objects are coordinatively manipulated at the same time. In addition, the ability to manipulate several target micro-objects independently and simultaneously opens up new opportunities to understanding how a group of cells or micro-objects behaves and communicates as a whole. Besides, it 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.

This paper proposes a robotic control technique for coordinative and simultaneous manipulation of multiple microscopic objects using laser-stage coordination, which is beyond the capability of current manipulation tech-

Fig. 2. An illustration of a virtual micro-hand formed by several laser-driven fingertips. (a) Several trappable micro-particles are trapped by using laser tweezers, then (b) the trapped micro-particles are utilized as laser-driven fingertips for grasping and manipulation of a target micro-object.

niques for optical tweezers. In the proposed technique, multiple laser beams are first generated and employed to trap identical and trappable micro-particles, in which each micro-particle is trapped by a single laser tweezer. Each of the trapped micro-particles is then driven by using the corresponding laser tweezer; and therefore, by manipulation of the laser tweezers, each of the trapped micro-particle thus functions as a special laser-driven fingertip in manipulation of the target micro-objects. Afterward, several micro-hands are constructed by coordinating multiple laser-driven fingertips, and then utilized for individual and coordinative manipulation of the target micro-objects. An illustration of a virtual micro-hand formed by several laser-driven fingertips for grasping and manipulation of a target micro-object is shown in Fig. 2. Simultaneously, global manipulation of all the target objects are performed by controlling the robot-assisted stage. An illustration of the control objective for coordinative and simultaneous manipulation of the grasped target micro-objects using multi-fingered micro-hands and the robot-assisted stage is shown in Fig. 3.

To be specific, cooperative control of several micro-hands and the robot-assisted stage are utilized for achieving the control objective, which can be summarized as follows:

- i. Local control objective: Individual and coordinative manipulation of the target micro-objects by coordinating micro-hands with multiple laser-driven fingertips. Several multi-fingered micro-hands are coordinated to grasp and individually manipulate the target objects, and at the same time, guarantee collision-free movement between the laser-driven fingertips during manipulation.
- ii. Global control objective: Group manipulation of all the target objects by maneuvering the robot-assisted stage which serves as the robotic manipulator. All the target objects are transported as a whole while being grasped by the micro-hands.

An example of the laser-stage coordination to perform a specific manipulation task is illustrated in Fig. 4. In

Fig. 3. An illustration of the control objective for coordinative and simultaneous manipulation of the grasped micro-objects using multi-fingered micro-hands and robot-assisted stage. It is noted that by moving the robot-assisted stage while maintaining stable grasps of the target objects, the relative positions of the target objects with respect to the robot-assisted stage will be varied.

Fig. 4. An example of the laser-stage coordination to perform a manipulation task. In this manipulation task, two target microscopic objects are grasped and then individually and coordinatively brought into contact with each other by using laser-driven fingertips, while ensuring collision-free movement between the laser-driven fingertips. Simultaneously, robot-assisted stage control is utilized to transport these two micro-objects into a desired region which is outside of the current field of view of the camera.

this manipulation task, two target microscopic objects are grasped and then brought into contact with each other by using laser-driven fingertips, and simultaneously, robot-assisted stage control is utilized to drive these two micro-objects into a desired region which can be outside of the current field of view of the camera. Another example is formation control of the grasped target objects as illustrated in Fig. 5. In this manipulation task, the formation of the target objects is formed while they are being kept inside a desired region (such as a ring

Fig. 5. Formation control of the target micro-objects. In this manipulation task, the formation of the target objects is formed while they are being kept inside a desired region which is specified as a ring. Interactions between the laser-driven fingertips are utilized for maintaining a preferred distance between the target objects. Simultaneously, robot-assisted stage control can also be utilized to drive the formation of the target objects to beyond the current field of view of the camera.

in Fig. 5), while interactions between the laser-driven fingertips are utilized for maintaining a preferred distance between the target objects. Simultaneously, robot-assisted stage control can also be utilized to drive the formation of the target objects to beyond the current field of view of the camera.

In this paper, the coordinate specification of the proposed control problem is illustrated in Fig. 6. The stage coordinate frame $\sum_S$ is defined together with the robot-assisted stage and moving with the stage, and the reference frame $\sum_C$ is defined to be fixed with the field of view (FOV) of the workspace. In this control problem, both the positions of the laser-driven fingertips and the target micro-objects are specified with respect to the stage coordinate frame $\sum_S$, and the positions of the laser tweezers are specified according to the reference frame $\sum_C$.

The dynamic equation of the robot-assisted stage which acts as the robotic manipulator is described as follows [21]:

$$\mathbf{M}\ddot{\mathbf{z}} + \mathbf{B}\dot{\mathbf{z}} = \mathbf{u}, \quad (1)$$

where diagonal and positive definite matrices $\mathbf{M} \in \mathbb{R}^{2 \times 2}$ and $\mathbf{B} \in \mathbb{R}^{2 \times 2}$ denote the inertia matrix and the damping matrix, respectively, $\mathbf{u} \in \mathbb{R}^2$ is the control input for the robot-assisted stage, and $\mathbf{z}$ is defined as the relative position of the FOV with respect to the stage coordinate frame $\sum_S$. The dynamics of the robot-assisted stage can be linearly parameterized as [32]:

$$\mathbf{M}\ddot{\mathbf{z}} + \mathbf{B}\dot{\mathbf{z}} = \mathbf{\Gamma}_z(\dot{\mathbf{z}}, \ddot{\mathbf{z}})\theta_z, \quad (2)$$

in which θ_z is an unknown parameter vector and $\mathbf{\Gamma}_z(\dot{\mathbf{z}}, \ddot{\mathbf{z}})$ is a known regressor matrix.

During the course of manipulation, each laser-driven fingertip experiences the following forces: (i) The viscous force induced by the viscosity of the fluid medium that tends to oppose the motion of the fingertip. (ii) The trapping force acting from the laser tweezer. (iii) The contact force exerting from the target object. The dynamics of the laser-driven fingertips i of micro-hands k ,

Fig. 6. The coordinate specification of the control system. The '+' signs denote the positions of the laser beams.

$k = 1, 2, \dots, n$, are thus described as follows:

$$\begin{cases} \text{Micro-hand 1: } \mathbf{B}_{f1}\dot{\mathbf{y}}_{1i} - \kappa_1((\mathbf{q}_{1i} + \mathbf{z}) - \mathbf{y}_{1i}) - \mathbf{f}_{1i} = 0, \\ \quad \quad \quad i = 1, 2, \dots, n_1, \\ \vdots \\ \text{Micro-hand } n: \mathbf{B}_{fn}\dot{\mathbf{y}}_{ni} - \kappa_n((\mathbf{q}_{ni} + \mathbf{z}) - \mathbf{y}_{ni}) - \mathbf{f}_{ni} = 0, \\ \quad \quad \quad i = 1, 2, \dots, n_n \end{cases} \quad (3)$$

where n is the number of the target micro-objects. The term $\mathbf{y}_{ki} = [y_{ki1}, y_{ki2}]^T \in \mathbb{R}^2$ is the position of the i^{th} fingertip of the k^{th} micro-hand, y_{ki} , in which $i = 1, 2, \dots, n_k$, with n_k is the number of the fingertips of the k^{th} micro-hand, and $\mathbf{q}_{ki} = [q_{ki1}, q_{ki2}]^T \in \mathbb{R}^2$ is the position of the corresponding laser tweezer that is utilized to trap and drive the fingertip y_{ki} . The parameters κ_k represent the stiffnesses of the laser tweezers, and $\mathbf{B}_{fk} = \text{diag}\{b_{fk1}, b_{fk2}\} \in \mathbb{R}^{2 \times 2}$ denote the diagonal and positive definite damping matrices with b_{fk1} and b_{fk2} are drag coefficients in horizontal and vertical axes, respectively. The trapping force of the laser tweezer is proportional to the small displacement between the position of the laser tweezer and the position of the trapped micro-particle, which is represented by $((\mathbf{q}_{ki} + \mathbf{z}) - \mathbf{y}_{ki})$ as illustrated in Fig. 6. The term $\mathbf{f}_{ki}$ is the contact force acting from the target object k on the fingertip i with $i = 1, 2, \dots, n_k$. Note that in micro-manipulation, the inertia of the micro-particle can be ignored due to the dominance of drag force.

Each target object is grasped and manipulated by several fingertips of each virtual micro-hand as illustrated in Fig. 3, Fig. 4, and Fig. 5, and therefore the dynamic equations of the target objects k , $k = 1, 2, \dots, n$, are expressed as follows:

$$\begin{cases} \text{Target object 1: } \mathbf{B}_{o1}\dot{\mathbf{x}}_1 = - \sum_{i=1}^{n_1} \mathbf{f}_{1i} \\ \vdots \\ \text{Target object } n: \mathbf{B}_{on}\dot{\mathbf{x}}_n = - \sum_{i=1}^{n_n} \mathbf{f}_{ni} \end{cases} \quad (4)$$

where $\mathbf{B}_{ok} \in \mathbb{R}^{2 \times 2}$, $k = 1, 2, \dots, n$, denote the diagonal and positive definite damping matrices, and $\mathbf{x}_k = [x_{k1}, x_{k2}]^T \in \mathbb{R}^2$ are the positions of the target objects k , $k = 1, 2, \dots, n$, with respect to the stage coordinate frame $\sum_S$.

3 Robotic Control Technique for Coordinative and Mobile Manipulation of Multiple Microscopic Objects using Multi-fingered Micro-hands and Robot-assisted Stage

In this section, cooperative control of multi-fingered micro-hands and robot-assisted stage is developed to achieve automated coordination and mobile manipulation of multiple microscopic objects. In this control technique, several virtual micro-hands with multiple laser-driven fingertips are utilized to grasp and coordinatively manipulate all the target objects into a desired dynamic region, and at the same time, maintaining the minimum distances between the fingertips to avoid collisions. Simultaneously, robot-assisted stage control are employed for group transportation of all the grasped target objects.

3.1 Dynamic Interaction between Micro-hands and Target Objects

In this subsection, we formulate the dynamic interactions between the laser-driven fingertips and the grasped target microscopic objects. From (3), the dynamic equations for n_k fingertips of all micro-hands can thus be represented as follows:

$$\begin{cases} \mathbf{B}_{h1}\dot{\mathbf{y}}_1 + \mathbf{K}_1(\mathbf{y}_1 - \mathbf{A}_1^T \mathbf{z}) = \mathbf{K}_1 \mathbf{q}_1 + \mathbf{f}_1 \\ \vdots \\ \mathbf{B}_{hn}\dot{\mathbf{y}}_n + \mathbf{K}_n(\mathbf{y}_n - \mathbf{A}_n^T \mathbf{z}) = \mathbf{K}_n \mathbf{q}_n + \mathbf{f}_n \end{cases} \quad (5)$$

where $\mathbf{B}_{hk} = \text{diag}\{\mathbf{B}_{fk}, \dots, \mathbf{B}_{fk}\} \in \mathbb{R}^{2n_k \times 2n_k}$ and $\mathbf{K}_k = \text{diag}\{\kappa_k \mathbf{I}_2, \dots, \kappa_k \mathbf{I}_2\} \in \mathbb{R}^{2n_k \times 2n_k}$ are diagonal and positive definite matrices with $\mathbf{I}_2 \in \mathbb{R}^{2 \times 2}$ is an identity matrix, and $\mathbf{f}_k = [\mathbf{f}_{k1}^T, \dots, \mathbf{f}_{kn_k}^T]^T \in \mathbb{R}^{2n_k \times 1}$, $\mathbf{q}_k = [\mathbf{q}_{k1}^T, \dots, \mathbf{q}_{kn_k}^T]^T \in \mathbb{R}^{2n_k \times 1}$, $\mathbf{y}_k = [\mathbf{y}_{k1}^T, \dots, \mathbf{y}_{kn_k}^T]^T \in \mathbb{R}^{2n_k \times 1}$, and $\mathbf{A}_k = [\mathbf{I}_2, \dots, \mathbf{I}_2] \in \mathbb{R}^{2 \times 2n_k}$.

Next, note that the last terms on the right hand side of (4) can be represented as:

$$\begin{cases} -\sum_{i=1}^{n_1} \mathbf{f}_{1i} = -\mathbf{A}_1 \mathbf{f}_1 \\ \vdots \\ -\sum_{i=1}^{n_n} \mathbf{f}_{ni} = -\mathbf{A}_n \mathbf{f}_n \end{cases} \quad (6)$$

where $\mathbf{A}_k = [\mathbf{I}_2, \dots, \mathbf{I}_2] \in \mathbb{R}^{2 \times 2n_k}$ are defined in (5). As the micro-hands are formed to grasp the target objects, the grasping formation of each micro-hand and a grasped target object can be considered as a rigid body. Assume that the center of the grasping formation generated by the laser-driven fingertips corresponds to the center of

mass of the corresponding target object, the velocities of the target objects k are described as follows:

$$\begin{cases} \dot{\mathbf{x}}_1 = \frac{1}{n_1} \sum_{i=1}^{n_1} \dot{\mathbf{y}}_{1i} = \frac{1}{n_1} \mathbf{A}_1 \dot{\mathbf{y}}_1 \\ \vdots \\ \dot{\mathbf{x}}_n = \frac{1}{n_n} \sum_{i=1}^{n_n} \dot{\mathbf{y}}_{ni} = \frac{1}{n_n} \mathbf{A}_n \dot{\mathbf{y}}_n \end{cases} \quad (7)$$

Multiplying both sides of (5) with $\mathbf{A}_k$, and using (4), (6), and (7), we thus have:

$$\begin{cases} (\mathbf{A}_1 \mathbf{B}_{h1} + \frac{1}{n_1} \mathbf{B}_{o1} \mathbf{A}_1) \dot{\mathbf{y}}_1 + \mathbf{A}_1 \mathbf{K}_1 (\mathbf{y}_1 - \mathbf{A}_1^T \mathbf{z}) = \mathbf{A}_1 \mathbf{K}_1 \mathbf{q}_1 \\ \vdots \\ (\mathbf{A}_n \mathbf{B}_{hn} + \frac{1}{n_n} \mathbf{B}_{on} \mathbf{A}_n) \dot{\mathbf{y}}_n + \mathbf{A}_n \mathbf{K}_n (\mathbf{y}_n - \mathbf{A}_n^T \mathbf{z}) = \mathbf{A}_n \mathbf{K}_n \mathbf{q}_n \end{cases} \quad (8)$$

3.2 Dynamic Region Reaching of the Target Microscopic Objects

In this control technique, virtual micro-hands with multiple laser-driven fingertips are utilized to individually and coordinatively drive the target microscopic objects into a desired dynamic region. By using the region control technique [33], a group of multiple target microscopic objects can be manipulated at the same time while their specific positions within the desired region are not required. It also enhances the flexibility in manipulation of multiple micro-objects. The desired dynamic region for the local control objective can be specified by the following inequalities:

$$h(\Delta \mathbf{X}_k) = \begin{bmatrix} h_1(\Delta \mathbf{X}_k) \\ h_2(\Delta \mathbf{X}_k) \\ \vdots \\ h_m(\Delta \mathbf{X}_k) \end{bmatrix} \leq 0, \quad (9)$$

where $\Delta \mathbf{X}_k = [\Delta X_{k1}, \Delta X_{k2}]^T = \mathbf{S}^{-1}(\mathbf{x}_k - \mathbf{x}_o) = \mathbf{S}^{-1} \Delta \mathbf{x}_k$ with the time-varying scaling matrix $\mathbf{S}$ which is invertible and differentiable, and $\mathbf{x}_o = [x_{o1}, x_{o2}]^T \in \mathbb{R}^2$ is the reference point of the desired region. Note that $h(\Delta \mathbf{X}_k)$ is a set of all the scalar functions $h_l(\Delta \mathbf{X}_k)$ with $l = 1, 2, \dots, m$ whose partial derivatives are continuous and m is the total number of the sub-regions. Also, it is noted that the desired region $h(\Delta \mathbf{X}_k)$ is defined as the intersections of all the sub-regions $h_l(\Delta \mathbf{X}_k)$, $l = 1, 2, \dots, m$. A desired region in a form of an ellipse, for example, can be specified as follows:

$$h_1(\Delta \mathbf{X}_k) = \frac{\{\Delta X_{k1}\}^2}{a_1^2} + \frac{\{\Delta X_{k2}\}^2}{a_2^2} - 1 \leq 0, \quad (10)$$

with a_1 and a_2 are positive constants. Another example of a rectangle region is specified as following inequalities:

$$\begin{cases} h_1(\Delta \mathbf{X}_k) = \{\Delta X_{k1}\}^2 - b_1^2 \leq 0 \\ h_2(\Delta \mathbf{X}_k) = \{\Delta X_{k2}\}^2 - b_2^2 \leq 0 \end{cases} \quad (11)$$

with b_1 and b_2 are positive constants. Also, a desired region of a ring, which is illustrated in Fig. 5, can be specified as:

$$\begin{cases} h_1(\Delta \mathbf{X}_k) = \{\Delta X_{k1}\}^2 + \{\Delta X_{k2}\}^2 - r_1^2 \leq 0 \\ h_2(\Delta \mathbf{X}_k) = r_2^2 - \{\Delta X_{k1}\}^2 - \{\Delta X_{k2}\}^2 \leq 0 \end{cases} \quad (12)$$

with r_1 and r_2 are positive constants in which $r_1 > r_2$. It is worth noting that the size of the desired dynamic region can be adjusted by using the scaling mapping $\mathbf{S}$. An example of the scaling matrix $\mathbf{S}$ is given as follows:

$$\mathbf{S} = \begin{bmatrix} s_x(t) & 0 \\ 0 & s_y(t) \end{bmatrix}, \quad (13)$$

where $s_x(t)$ and $s_y(t)$ are scaling factors.

A potential energy function for the local control objective of moving each target object k into the desired region is thus defined as:

$$Q_k = \sum_{l=1}^m \frac{\lambda_l}{\beta} [\max(0, h_l(\Delta \mathbf{X}_k))]^\beta, \quad (14)$$

with a constant integer β is chosen as $\beta > 2$ so that Q_k is at least twice differentiable, and λ_l is a positive constant. An illustration of the potential energy function for the local control objective described in (14) is shown in Fig. 7(a).

A region error $\Delta \xi_k$ of each target object k is thus specified as follows:

$$\begin{aligned} \Delta \xi_k &= \frac{\partial Q_k}{\partial (\Delta \mathbf{X}_k)} \\ &= \sum_{l=1}^m \lambda_l [\max(0, h_l(\Delta \mathbf{X}_k))]^{\beta-1} \left(\frac{\partial h_l(\Delta \mathbf{X}_k)}{\partial (\Delta \mathbf{X}_k)} \right)^T. \end{aligned} \quad (15)$$

When the target object k is outside of the desired region, the control force which is directly proportional to the region error is activated, and thus driving the target object towards the region. When the target object is inside the desired region, $\Delta \xi_k = 0$, and the control force is also eliminated.

Fig. 7. Illustrations of the potential energy functions for: (a) the local control objective of moving the target objects into the desired region (b) collision-free movement of the fingertips.

3.3 Formation Control and Repositioning of the Laser-driven Fingertips for Maintaining Grasping Formations of the Target Objects

In this section, formation control of the laser-driven fingertips of each individual micro-hand is performed to maintain the grasping formation of the target object. It also means that the formation of the fingertips that grasp a specific target object must be maintained during the course manipulation. Examples of maintaining the formations generated by the fingertips to grasp and manipulate the target objects are shown in Fig. 8.

Let us first define a task function $g_{kikj}(\Delta \mathbf{y}_{kikj})$ involving any two arbitrary fingertips ki and kj that grasp the target object k as follows:

$$g_{kikj}(\Delta \mathbf{y}_{kikj}) = \|\Delta \mathbf{y}_{kikj}\|^2 - \|\Delta \mathbf{Y}_{kikj0}\|^2, \quad (16)$$

where $\Delta \mathbf{y}_{kikj} = \mathbf{y}_{ki} - \mathbf{y}_{kj}$ with $\mathbf{y}_{ki}$ and $\mathbf{y}_{kj}$ are respectively the positions of the fingertips ki and kj , and $\Delta \mathbf{Y}_{kikj0} = \mathbf{S}_{kikj} \Delta \mathbf{y}_{kikj0}$ with $\mathbf{S}_{kikj} \in \mathbb{R}^{2 \times 2}$ is a time-varying scaling matrix, and $\Delta \mathbf{y}_{kikj0}$ is the desired distance between the two fingertips ki and kj . It is noted that by using the scaling matrix $\mathbf{S}_{kikj}$, the distance between each pair of the fingertips ki and kj can be adjusted, and therefore, the grasping formation of the fingertips that hold and move a specific target object can be restructured.

Fig. 8. Illustrations of the formations generated by the fingertips for grasping and manipulation of the target microscopical objects using (a) 3 fingertips (b) 5 fingertips.

Next, a potential energy function for each fingertip ki to maintain the grasping formation is given as follows:

$$P_{ki} = \frac{1}{2\chi} \sum_{j \in N_{ki}} \lambda_{kikj} [g_{kikj} (\Delta \mathbf{y}_{kikj})]^{2\chi}, \quad (17)$$

where χ is a positive integer so that P_{ki} is at least twice differentiable, and λ_{kikj} is a positive constant, and N_{ki} is the set of the fingertips that hold the target object k , except for the fingertip ki .

Partial differentiating the potential energy P_{ki} in (17) with respect to $\Delta \mathbf{y}_{kikj}$, we obtain:

$$\begin{aligned} \frac{\partial P_{ki}}{\partial (\Delta \mathbf{y}_{kikj})} &= \sum_{j \in N_{ki}} \lambda_{kikj} [g_{kikj} (\Delta \mathbf{y}_{kikj})]^{2\chi-1} \times \\ &\times \left(\frac{\partial g_{kikj} (\Delta \mathbf{y}_{kikj})}{\partial (\Delta \mathbf{y}_{kikj})} \right)^T = \sum_{j \in N_{ki}} \lambda_{kikj} \Delta \eta_{kikj} = \Delta \eta_{ki}. \end{aligned} \quad (18)$$

It is noted that the interaction term $\Delta \eta_{ki}$ is defined as the gradient of the potential energy function P_{ki} described in (17). Also note that $\Delta \eta_{ki}$ is corresponding to the resultant interactive force acting on the fingertip ki from all of its neighboring fingertips $j \in N_{ki}$. When the distance between two arbitrary fingertips ki and kj is remained unchanged as its desired distance, i.e. $\|\Delta \mathbf{y}_{kikj}\| = \|\Delta \mathbf{y}_{kikj0}\|$, there is no interactive force between the fingertips ki and kj as $\Delta \eta_{kikj} = 0$. When $\|\Delta \mathbf{y}_{kikj}\| \neq \|\Delta \mathbf{y}_{kikj0}\|$, the interactive force $\Delta \eta_{kikj}$ acting on the fingertip ki is then activated to maintain the desired distance between the fingertips ki and kj . Therefore, if all the scaling matrices $\mathbf{S}_{kikj}$ are chosen to be identity matrices, the distance between any pair of fingertips of a virtual micro-hand k are kept at its desired one, and the grasping formation generated by all the fingertips of that micro-hand are thus maintained to hold the target object.

Bringing cells or micro-objects into contact is a mandatory step in many applications, including the studies of cell-cell interactions, cell fusion, cell adhesion, etc. During the process of bringing the target cells or micro-objects into contact, there are fingertips that may block the contact points of the cells or micro-objects. In this paper, a primary study on repositioning strategy of the laser-driven fingertips is proposed to allow the fingertips in a grasping formation to be repositioned if necessary. In this approach, one or some fingertips can be released from the grasping formation while the rest of fingertips hold the target object. In order to release a fingertip ki from a grasping formation, all the scaling matrices

$$\mathbf{S}_{kikj} = \begin{bmatrix} s_{kikjx}(t) & 0 \\ 0 & s_{kikjy}(t) \end{bmatrix}, \quad (19)$$

where $j \in N_{ki}$ are adjusted appropriately, which make the changes in the relative distances between the fingertip ki and the rest of fingertips, and thus leading to the repositioning of the fingertip ki . Besides, in order to preserve the grasping formation of the target object k , all the scaling matrices for every pairs of the rest of fingertips are remained unchanged as identity matrices. It is worth noting that in order to maintain a grasping formation of a target object, at least two or three fingertips are required. Fig. 9 shows an illustration of the repositioning technique of the laser-driven fingertips to release one fingertip from the grasping formation. In this approach, the distances between the fingertips $k1$, $k2$, and $k3$ are kept fixed as all the scaling matrices $\mathbf{S}_{k1k2}$, $\mathbf{S}_{k1k3}$, and $\mathbf{S}_{k2k3}$ are set as identity matrices; and therefore, the grasping formation which is created by the fingertips $k1$, $k2$, and $k3$ are still remained to hold the target object. Besides, the fingertip $k4$ can be released from the grasping formation as the distances between the fingertip $k4$ and other fingertips are adjusted with the use of appropriate scaling matrices $\mathbf{S}_{k4k1}$, $\mathbf{S}_{k4k2}$, and $\mathbf{S}_{k4k3}$. Example of the scaling matrices $\mathbf{S}_{k4k1}$, $\mathbf{S}_{k4k2}$, and $\mathbf{S}_{k4k3}$ for repositioning of the fingertip $k4$ is chosen as:

$$\begin{aligned} s_{k4k1x} &= \left| \frac{\Delta y_{k4k1x}}{\Delta y_{k4k1x0} + \nu_{k4k1x}} \right| \\ &= \left| \frac{\Delta y_{k4k1x0} - \delta(t) \cos \omega(t) + c\delta(t) \sin \omega(t)}{\Delta y_{k4k1x0} + \nu_{k4k1x}} \right|, \end{aligned} \quad (20)$$

$$\begin{aligned} s_{k4k1y} &= \left| \frac{\Delta y_{k4k1y}}{\Delta y_{k4k1y0} + \nu_{k4k1y}} \right| \\ &= \left| \frac{\Delta y_{k4k1y0} + \delta(t) \sin \omega(t) + c\delta(t) \cos \omega(t)}{\Delta y_{k4k1y0} + \nu_{k4k1y}} \right|, \end{aligned} \quad (21)$$

and

$$\begin{aligned} s_{k4k2x} &= \left| \frac{\Delta y_{k4k2x}}{\Delta y_{k4k2x0} + \nu_{k4k2x}} \right| \\ &= \left| \frac{\Delta y_{k4k2x0} - \delta(t) \cos \omega(t) + c\delta(t) \sin \omega(t)}{\Delta y_{k4k2x0} + \nu_{k4k2x}} \right|, \end{aligned} \quad (22)$$

Fig. 9. Repositioning of the laser-driven fingertips. The fingertip $k4$ is released from the grasping formation as its distances with other fingertips are scaled, and at the same time, the grasping formation which is formed by the fingertips $k1$, $k2$, and $k3$ are remained to hold the target object.

$$s_{k4k2y} = \left| \frac{\Delta y_{k4k2y}}{\Delta y_{k4k2y0} + \nu_{k4k2y}} \right| = \left| \frac{\Delta y_{k4k2y0} - \delta(t) \sin \omega(t) - c\delta(t) \cos \omega(t)}{\Delta y_{k4k2y0} + \nu_{k4k2y}} \right|, \quad (23)$$

and

$$s_{k4k3x} = \left| \frac{\Delta y_{k4k3x}}{\Delta y_{k4k3x0} + \nu_{k4k3x}} \right| = \left| \frac{\Delta y_{k4k3x0} - \delta(t) \cos \omega(t) + c\delta(t) \sin \omega(t)}{\Delta y_{k4k3x0} + \nu_{k4k3x}} \right|, \quad (24)$$

$$s_{k4k3y} = \left| \frac{\Delta y_{k4k3y}}{\Delta y_{k4k3y0} + \nu_{k4k3y}} \right| = \left| \frac{\Delta y_{k4k3y0} - \delta(t) \sin \omega(t) - c\delta(t) \cos \omega(t)}{\Delta y_{k4k3y0} + \nu_{k4k3y}} \right|, \quad (25)$$

where s_{kikjx} and s_{kikjy} are respectively the scaling factors in horizontal and vertical axes, Δy_{k4k2y} and Δy_{k4k3y} , $j = 1, 2, 3$ are the distances in horizontal and vertical axes between fingertips $k4$ and fingertips kj while Δy_{k4k2y0} and Δy_{k4k3y0} , $j = 1, 2, 3$ are these distances when $k4$ is still in the grasping formation. In (20)-(25), ω is the angle of the moving direction of the grasping formation with respect to the stage coordinate frame $\sum_S$, as shown in Fig. 9. Also in (20)-(25), $\delta(t)$ is defined as $\delta(t) = |\mathbf{y}_{kj}(t) - \mathbf{y}_{kj}(t_0)|$, $j = 1, 2, 3$, which is the displacement of each fingertip kj when fingertip $k4$ starts being released from the grasping formation, and positive integer c defines the relative speed between the fingertip $k4$ and the grasping formation. Besides, ν_{k4k2y} and ν_{k4k3y} are utilized to deal with the cases when either Δy_{k4k2y0} or Δy_{k4k3y0} is equal to 0, respectively. To be specific, $\nu_{k4k2y} = 1$ when $\Delta y_{k4k2y0} = 0$, and when $\Delta y_{k4k2y0} \neq 0$, $\nu_{k4k2y} = 0$. Similarly, $\nu_{k4k3y} = 1$ when $\Delta y_{k4k3y0} = 0$, and when $\Delta y_{k4k3y0} \neq 0$, $\nu_{k4k3y} = 0$. With the use of these scaling matrices, the fingertip $k4$ is released perpendicularly from the grasping formation of the target object k , as shown in Fig. 9.

3.4 Collision Avoidance of the Micro-hands

Next, in order to avoid collisions between the micro-hands during manipulation, let us define an interactive term $g_{ki\bar{k}i}$ between the fingertip ki that grasps the target object k and any neighboring fingertip $\bar{k}i$ that grasps the target object $\bar{k}$ as follows:

$$g_{ki\bar{k}i}(\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i}) = r^2 - \|\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i}\|^2 \leq 0, \quad (26)$$

where r is a positive constant, and $\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i} = \mathbf{y}_{\mathbf{k}i} - \mathbf{y}_{\mathbf{k}i}$ with $\mathbf{y}_{\mathbf{k}i}$ and $\mathbf{y}_{\mathbf{k}i}$ are the positions of the fingertips ki and $\bar{k}i$, respectively.

Thus, the potential energy function for collisions avoidance between the fingertips from different micro-hands is specified as follows:

$$W_{ki} = \sum_{\bar{k}i \in N_{\bar{k}i}} \frac{\lambda_{ki\bar{k}i}}{\beta} \left[\max(0, g_{ki\bar{k}i}(\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i})) \right]^\beta, \quad (27)$$

where $\lambda_{ki\bar{k}i}$ is a positive constant, and $N_{\bar{k}i}$ is the set of the fingertips $\bar{k}i$ from all the neighboring micro-hands $\bar{k}$.

Partial differentiating the potential energy function W_{ki} in (27) with respect to $\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i}$, we obtain the interactive force for collisions avoidance between the fingertips from different micro-hands as follows:

$$\frac{\partial W_{ki}}{\partial (\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i})} = \sum_{\bar{k}i \in N_{\bar{k}i}} \lambda_{ki\bar{k}i} \left\{ \max(0, g_{ki\bar{k}i}(\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i})) \right\}^{\beta-1} \times \left(\frac{\partial g_{ki\bar{k}i}(\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i})}{\partial (\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i})} \right)^T = \sum_{\bar{k}i \in N_{\bar{k}i}} \lambda_{ki\bar{k}i} \Delta \psi_{ki\bar{k}i}. \quad (28)$$

Property 1. The interactive forces for collisions avoidance between different fingertips, which is the gradient of the potential energy function W_{ki} described in (27) and Fig. 7(b), are upper bounded, i.e. $\|\Delta \psi_{ki\bar{k}i}\| < c$ with a positive constant c .

Next, an adaptive force for collisions avoidance between micro-hands is defined as

$$\Delta \rho_{ki} = \sum_{\bar{k}i \in N_{\bar{k}i}} \lambda_{ki\bar{k}i} \Re(\theta_{ki\bar{k}i}) \Delta \psi_{ki\bar{k}i} = \sum_{\bar{k}i \in N_{\bar{k}i}} \lambda_{ki\bar{k}i} \Delta \rho_{ki\bar{k}i}, \quad (29)$$

where $\theta_{ki\bar{k}i}$ is rotational angle, and $\Re(\theta_{ki\bar{k}i})$ is rotational matrix which is specified as follows:

$$\Re(\theta_{ki\bar{k}i}) = \begin{bmatrix} \cos(\theta_{ki\bar{k}i}) & \sin(\theta_{ki\bar{k}i}) \\ -\sin(\theta_{ki\bar{k}i}) & \cos(\theta_{ki\bar{k}i}) \end{bmatrix}. \quad (30)$$

It is noted that $\Delta \rho_{ki}$ corresponds to the resultant interactive force exerting on the fingertip ki from all the fingertips $\bar{k}i$ from all the neighboring micro-hands $\bar{k}$. When the fingertip ki maintains a minimum distance with any fingertip $\bar{k}i$, i.e. $\|\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i}\| \geq r$, then $\Delta \rho_{ki\bar{k}i} = 0$. When the distance between the fingertip ki and any of the fingertips from the neighboring hands is less than the minimum distance, i.e. $\|\Delta \mathbf{y}_{\mathbf{k}i\mathbf{k}i}\| < r$, the control force $\Delta \rho_{ki\bar{k}i}$ is activated to maintain the minimum distance between the laser-driven fingertips, and thus ensure collision-free movement of the fingertips during manipulation. Besides, it is worth noting that the positive

constant r defined in (26) can also be utilized for maintaining the relative distances between the target objects, as illustrated in Fig. 10, and thus formation control of the target objects can be achieved.

3.5 Cooperative and Mobile Manipulation of Multiple Micro-objects based on Micro-hands and Laser-Stage Control

This subsection aims to develop the controllers for the laser-driven fingertips and the robot-assisted stage to achieve control objective of coordinative and simultaneous manipulation of multiple microscopic objects.

To achieve the control objective, the development of the controllers can be resolved as follows. (i) In order to achieve the local control objective, the control input $\mathbf{q}_{\mathbf{k}i}$ of the laser-driven system is proposed based on the dynamic equation (8) to drive all the target objects into the desired dynamic region, while ensuring the collision-free movement of the multi-fingered micro-hands. (ii) In order to achieve the global control objective, the control input $\mathbf{u}$ of the robotic manipulator is developed based on the dynamic equation (1) to drive the robot-assisted stage such that all the target objects are transported as a whole group.

3.5.1 Independent and Coordinative Manipulation of Multiple Micro-objects using Micro-hands with Laser-driven Fingertips

In this part, the control input for the laser-driven system is developed to achieve the control objectives of driving all the target objects into a desired dynamic region, and concurrently, guarantee the collision-free movement of the fingertips during the course of manipulation.

Fig. 10. Example of considering the interactions between the laser-driven fingertips from different micro-hands for maintaining a preferred distances between the target objects.

Since

$$\begin{aligned}\mathbf{A}_k \mathbf{B}_{hk} &= (\mathbf{I}_2, \dots, \mathbf{I}_2) \text{diag}\{\mathbf{B}_{fk}, \dots, \mathbf{B}_{fk}\} \\ &= (\mathbf{B}_{fk}, \dots, \mathbf{B}_{fk}) = \mathbf{B}_{fk} \mathbf{A}_k,\end{aligned}\quad (31)$$

then using (7), we thus have

$$\begin{aligned}(\mathbf{A}_k \mathbf{B}_{hk} + \frac{1}{n_k} \mathbf{B}_{ok} \mathbf{A}_k) \dot{\mathbf{y}}_k &= (\mathbf{B}_{fk} + \frac{1}{n_k} \mathbf{B}_{ok}) \mathbf{A}_k \dot{\mathbf{y}}_k \\ &= (n_k \mathbf{B}_{fk} + \mathbf{B}_{ok}) \dot{\mathbf{x}}_k.\end{aligned}\quad (32)$$

Hence, (8) can be rewritten as:

$$\begin{cases} \dot{\mathbf{x}}_1 + (n_1 \mathbf{B}_{f1} + \mathbf{B}_{o1})^{-1} \mathbf{A}_1 \mathbf{K}_1 (\mathbf{y}_1 - \mathbf{A}_1^T \mathbf{z}) \\ = (n_1 \mathbf{B}_{f1} + \mathbf{B}_{o1})^{-1} \mathbf{A}_1 \mathbf{K}_1 \mathbf{q}_1 \\ \vdots \\ \dot{\mathbf{x}}_n + (n_n \mathbf{B}_{fn} + \mathbf{B}_{on})^{-1} \mathbf{A}_n \mathbf{K}_n (\mathbf{y}_n - \mathbf{A}_n^T \mathbf{z}) \\ = (n_n \mathbf{B}_{fn} + \mathbf{B}_{on})^{-1} \mathbf{A}_n \mathbf{K}_n \mathbf{q}_n \end{cases}\quad (33)$$

The reference vectors of the target micro-objects are specified as:

$$\begin{cases} \dot{\mathbf{x}}_{r1} = \dot{\mathbf{x}}_o - \mathbf{S} \frac{d}{dt} (\mathbf{S}^{-1}) (\mathbf{x}_1 - \mathbf{x}_o) \\ \vdots \\ \dot{\mathbf{x}}_{rn} = \dot{\mathbf{x}}_o - \mathbf{S} \frac{d}{dt} (\mathbf{S}^{-1}) (\mathbf{x}_n - \mathbf{x}_o) \end{cases}\quad (34)$$

Then (33) can be rewritten as:

$$\begin{cases} \mathbf{S} \Delta \dot{\mathbf{x}}_1 + \dot{\mathbf{x}}_{r1} + (n_1 \mathbf{B}_{f1} + \mathbf{B}_{o1})^{-1} \mathbf{A}_1 \mathbf{K}_1 (\mathbf{y}_1 - \mathbf{A}_1^T \mathbf{z}) \\ = (n_1 \mathbf{B}_{f1} + \mathbf{B}_{o1})^{-1} \mathbf{A}_1 \mathbf{K}_1 \mathbf{q}_1 \\ \vdots \\ \mathbf{S} \Delta \dot{\mathbf{x}}_n + \dot{\mathbf{x}}_{rn} + (n_n \mathbf{B}_{fn} + \mathbf{B}_{on})^{-1} \mathbf{A}_n \mathbf{K}_n (\mathbf{y}_n - \mathbf{A}_n^T \mathbf{z}) \\ = (n_n \mathbf{B}_{fn} + \mathbf{B}_{on})^{-1} \mathbf{A}_n \mathbf{K}_n \mathbf{q}_n \end{cases}\quad (35)$$

where $\Delta \dot{\mathbf{x}}_k = \frac{d}{dt} (\mathbf{S}^{-1} \Delta \mathbf{x}_k)$ with $\Delta \mathbf{x}_k$ are defined in (9). The control inputs for the laser driven system are derived as follows:

$$\begin{cases} \mathbf{q}_{1i} = \mathbf{y}_{1i} - \mathbf{z} + \frac{1}{n_1} \dot{\mathbf{x}}_{r1} - k_q \mathbf{S}^{-T} (\Delta \xi_1 + \alpha \eta_{1i} + \gamma \rho_{1i}) \\ + \frac{1}{n_1} \Gamma (\dot{\mathbf{x}}_{r1}) \hat{\varphi}_1 \\ \vdots \\ \mathbf{q}_{ni} = \mathbf{y}_{ni} - \mathbf{z} + \frac{1}{n_n} \dot{\mathbf{x}}_{rn} - k_q \mathbf{S}^{-T} (\Delta \xi_n + \alpha \eta_{ni} + \gamma \rho_{ni}) \\ + \frac{1}{n_n} \Gamma (\dot{\mathbf{x}}_{rn}) \hat{\varphi}_n \end{cases}\quad (36)$$

where $i = 1, 2, \dots, n_k$, α and γ are positive constants, and k_q are positive gains. The first two elements in the right hand sides of (36) are utilized to compensate for

the positions of the laser-driven fingertips with respect to the reference frame $\sum_C$. The third elements in the right hand sides of (36), $\frac{1}{n_k} \dot{\mathbf{x}}_{\mathbf{rk}}$, are the reference velocity vectors, as defined in (34). The control forces $-k_q \mathbf{S}^{-T} \Delta \xi_k$, $-\alpha k_q \mathbf{S}^{-T} \eta_{ki}$, and $-\gamma k_q \mathbf{S}^{-T} \rho_{ki}$ are utilized to drive the target micro-objects towards the desired region, to maintain the grasping formations of the fingertips, and to ensure collision avoidance between the fingertips, respectively. The adaptive regressors $\mathbf{\Gamma}(\dot{\mathbf{x}}_{\mathbf{rk}})$ [34] are diagonal matrices whose diagonal elements are the entries of the reference vectors $\dot{\mathbf{x}}_{\mathbf{rk}}$, i.e. $\mathbf{\Gamma}(\dot{\mathbf{x}}_{\mathbf{rk}}) = \text{diag}\{\dot{x}_{rk1}, \dot{x}_{rk2}\}$, and $\hat{\varphi}_k \in \mathbb{R}^2$ are the adaptive parameter vectors whose updating laws are given as:

$$\begin{cases} \dot{\hat{\varphi}}_1 = -\mathbf{L}_1 \mathbf{\Gamma}(\dot{\mathbf{x}}_{\mathbf{r1}}) \mathbf{S}^{-T} \Delta \xi_1 \\ \vdots \\ \dot{\hat{\varphi}}_n = -\mathbf{L}_n \mathbf{\Gamma}(\dot{\mathbf{x}}_{\mathbf{rn}}) \mathbf{S}^{-T} \Delta \xi_n \end{cases} \quad (37)$$

where $\mathbf{L}_k \in \mathbb{R}^{2 \times 2}$ are positive diagonal matrices. It is noted that in (36), $\mathbf{\Gamma}(\dot{\mathbf{x}}_{\mathbf{rk}})$ and $\hat{\varphi}_k$ are used to compensate the uncertainty caused by the unknown parameters κ_k , $\mathbf{B}_{\mathbf{fk}}$, and $\mathbf{B}_{\mathbf{ok}}$. In (36), the superscript $-T$ represents the inverse transpose of a matrix. Substituting (36) into (35), we get the closed-loop equations:

$$\begin{cases} \mathbf{S} \Delta \dot{\mathbf{x}}_1 + (\mathbf{I}_2 - \mathbf{\Omega}_1) \dot{\mathbf{x}}_{\mathbf{r1}} - \mathbf{\Omega}_1 \mathbf{\Gamma}(\dot{\mathbf{x}}_{\mathbf{r1}}) \hat{\varphi}_1 \\ + k_q \mathbf{\Omega}_1 \mathbf{S}^{-T} \left[n_1 \Delta \xi_1 + \sum_{i=1}^{n_1} (\alpha \eta_{1i} + \gamma \rho_{1i}) \right] = \mathbf{0} \\ \vdots \\ \mathbf{S} \Delta \dot{\mathbf{x}}_n + (\mathbf{I}_2 - \mathbf{\Omega}_n) \dot{\mathbf{x}}_{\mathbf{rn}} - \mathbf{\Omega}_n \mathbf{\Gamma}(\dot{\mathbf{x}}_{\mathbf{rn}}) \hat{\varphi}_n \\ + k_q \mathbf{\Omega}_n \mathbf{S}^{-T} \left[n_n \Delta \xi_n + \sum_{i=1}^{n_n} (\alpha \eta_{ni} + \gamma \rho_{ni}) \right] = \mathbf{0} \end{cases} \quad (38)$$

where $\mathbf{\Omega}_k = \kappa_k (n_k \mathbf{B}_{\mathbf{fk}} + \mathbf{B}_{\mathbf{ok}})^{-1}$ are diagonal matrices which are positive definite.

3.5.2 Global Manipulation of the Target Micro-objects by Maneuvering the Robot-assisted Stage

In the previous part, control inputs for the laser-driven fingertips have been developed for individual and coordinative manipulation of the grasped target objects. In this part, robot-assisted stage control is utilized for global manipulation of all the grasped target micro-objects. The robot-assisted stage is maneuvered to follow a desired trajectory which specifies the desired motion for the whole configuration of the target micro-objects.

First, a reference vector is specified for the robot-assisted stage as:

$$\dot{\mathbf{z}}_r = \dot{\mathbf{z}}_d - \sigma \Delta \mathbf{z}, \quad (39)$$

where $\Delta \mathbf{z} = \mathbf{z} - \mathbf{z}_d$ with $\mathbf{z}_d$ is the desired trajectory of the robot-assisted stage, and σ is a positive constant.

Then we define a sliding vector $\mathbf{s}$ for the robot-assisted stage as:

$$\mathbf{s} = \dot{\mathbf{z}} - \dot{\mathbf{z}}_r \quad (40)$$

The dynamics of the robot-assisted stage (1) is thus rewritten as follows:

$$\mathbf{M} \dot{\mathbf{s}} + \mathbf{B} \mathbf{s} + \mathbf{\Gamma}_z(\dot{\mathbf{z}}_r, \ddot{\mathbf{z}}_r) \theta_z = \mathbf{u}, \quad (41)$$

where $\theta_z \in \mathbb{R}^{p \times 1}$ is a parameter vector, and $\mathbf{\Gamma}_z(\dot{\mathbf{z}}_r, \ddot{\mathbf{z}}_r) \in \mathbb{R}^{2 \times p}$ is a regressor matrix.

The control input $\mathbf{u}$ for the robot-assisted stage is derived as follows:

$$\mathbf{u} = -\mathbf{K}_s \mathbf{s} + \mathbf{\Gamma}_z(\dot{\mathbf{z}}_r, \ddot{\mathbf{z}}_r) \hat{\theta}_z, \quad (42)$$

where $\mathbf{K}_s \in \mathbb{R}^{2 \times 2}$ is a diagonal matrix which is positive definite, and $\hat{\theta}_z$ is the estimation of θ_z whose updating law is specified by:

$$\dot{\hat{\theta}}_z = -\mathbf{L}_s \mathbf{\Gamma}_z^T(\dot{\mathbf{z}}_r, \ddot{\mathbf{z}}_r) \mathbf{s}, \quad (43)$$

where $\mathbf{L}_s \in \mathbb{R}^{\mu \times \mu}$ is a symmetric and positive definite matrix. It is noted that the last term in (42) is utilized to compensate for the uncertainty of the dynamics of the robot-assisted stage.

Substituting (42) into (41), the closed-loop dynamic equation for the global manipulation task is thus derived as:

$$\mathbf{M} \dot{\mathbf{s}} + (\mathbf{B} + \mathbf{K}_s) \mathbf{s} + \mathbf{\Gamma}_z(\dot{\mathbf{z}}_r, \ddot{\mathbf{z}}_r) \Delta \theta_z = \mathbf{0}, \quad (44)$$

where $\Delta \theta_z = \theta_z - \hat{\theta}_z$.

3.6 Stability analysis

This subsection aims to analyze the stability of the overall closed-loop control system described by (38) and (44). First, all the second terms of (38) are rewritten as:

$$\begin{aligned} (\mathbf{I}_2 - \mathbf{\Omega}_k) \dot{\mathbf{x}}_{\mathbf{rk}} &= \text{diag}\{1 - \Omega_{k1}, 1 - \Omega_{k2}\} (\dot{x}_{rk1}, \dot{x}_{rk2})^T \\ &= \text{diag}\{\dot{x}_{rk1}, \dot{x}_{rk2}\} (1 - \Omega_{k1}, 1 - \Omega_{k2})^T = \mathbf{\Gamma}(\dot{\mathbf{x}}_{\mathbf{rk}}) \vartheta_k, \end{aligned} \quad (45)$$

where $\vartheta_k = (1 - \Omega_{k1}, 1 - \Omega_{k2})^T$ are unknown and bounded.

Substituting (45) into (38), yields:

$$\begin{cases} \mathbf{S}\Delta\dot{\mathbf{X}}_1 + \mathbf{\Gamma}(\dot{\mathbf{x}}_{r1})(\vartheta_1 - \mathbf{\Omega}_1\hat{\varphi}_1) \\ + k_q\mathbf{\Omega}_1\mathbf{S}^{-T} \left[n_1\Delta\xi_1 + \sum_{i=1}^{n_1} (\alpha\eta_{1i} + \gamma\rho_{1i}) \right] = \mathbf{0} \\ \vdots \\ \mathbf{S}\Delta\dot{\mathbf{X}}_n + \mathbf{\Gamma}(\dot{\mathbf{x}}_{rn})(\vartheta_n - \mathbf{\Omega}_n\hat{\varphi}_n) \\ + k_q\mathbf{\Omega}_n\mathbf{S}^{-T} \left[n_n\Delta\xi_n + \sum_{i=1}^{n_n} (\alpha\eta_{ni} + \gamma\rho_{ni}) \right] = \mathbf{0} \end{cases} \quad (46)$$

From (46) and (44), we obtain the overall closed-loop systems as follows:

$$\begin{cases} \mathbf{S}\Delta\dot{\mathbf{X}}_1 + \mathbf{\Gamma}(\dot{\mathbf{x}}_{r1})(\vartheta_1 - \mathbf{\Omega}_1\hat{\varphi}_1) \\ + k_q\mathbf{\Omega}_1\mathbf{S}^{-T} \left[n_1\Delta\xi_1 + \sum_{i=1}^{n_1} (\alpha\eta_{1i} + \gamma\rho_{1i}) \right] = \mathbf{0} \\ \vdots \\ \mathbf{S}\Delta\dot{\mathbf{X}}_n + \mathbf{\Gamma}(\dot{\mathbf{x}}_{rn})(\vartheta_n - \mathbf{\Omega}_n\hat{\varphi}_n) \\ + k_q\mathbf{\Omega}_n\mathbf{S}^{-T} \left[n_n\Delta\xi_n + \sum_{i=1}^{n_n} (\alpha\eta_{ni} + \gamma\rho_{ni}) \right] = \mathbf{0} \\ \mathbf{M}\dot{\mathbf{s}} + (\mathbf{B} + \mathbf{K}_s)\mathbf{s} + \mathbf{\Gamma}_z(\dot{\mathbf{z}}_r, \ddot{\mathbf{z}}_r)\Delta\theta_z = \mathbf{0} \end{cases} \quad (47)$$

A Lyapunov-like candidate function for analyzing the stability of the control system is proposed as:

$$V = V_{laser} + V_{stage}, \quad (48)$$

such that

$$V_{laser} = \sum_{k=1}^n \left[Q_k + \frac{1}{2} (\mathbf{\Omega}_k^{-1}\vartheta_k - \hat{\varphi}_k)^T \mathbf{L}_k^{-1} \mathbf{\Omega}_k (\mathbf{\Omega}_k^{-1}\vartheta_k - \hat{\varphi}_k) \right] \quad (49)$$

with Q_k defined in (14);

and

$$V_{stage} = \frac{1}{2} \mathbf{s}^T \mathbf{M} \mathbf{s} + \frac{1}{2} \Delta\theta_z^T \mathbf{L}_s^{-1} \Delta\theta_z, \quad (50)$$

Taking derivative of V with respect to time, yields:

$$\begin{aligned} \dot{V} &= \dot{V}_{laser} + \dot{V}_{stage} \\ &= \sum_{k=1}^n \sum_{l=1}^m \lambda_l [\max(0, h_l(\Delta\mathbf{X}_k))]^{\beta-1} \Delta\dot{\mathbf{X}}_k^T \left(\frac{\partial h_l(\Delta\mathbf{X}_k)}{\partial(\Delta\mathbf{X}_k)} \right)^T \\ &\quad - \sum_{k=1}^n \dot{\hat{\varphi}}_k^T \mathbf{L}_k^{-1} (\vartheta_k - \mathbf{\Omega}_k \hat{\varphi}_k) \\ &\quad + \mathbf{s}^T \mathbf{M} \dot{\mathbf{s}} - \dot{\theta}_z^T \mathbf{L}_s^{-1} \Delta\theta_z \\ &= \sum_{k=1}^n \left[\Delta\dot{\mathbf{X}}_k^T \Delta\xi_k - \dot{\hat{\varphi}}_k^T \mathbf{L}_k^{-1} (\vartheta_k - \mathbf{\Omega}_k \hat{\varphi}_k) \right] \\ &\quad + \mathbf{s}^T \mathbf{M} \dot{\mathbf{s}} - \dot{\theta}_z^T \mathbf{L}_s^{-1} \Delta\theta_z. \end{aligned} \quad (51)$$

Substituting the update laws in (37), (43) and the closed-loop dynamics equations in (47) into (51), we obtain:

$$\begin{aligned} \dot{V} &= - \sum_{k=1}^n \left[\{ \mathbf{S}^{-1} \mathbf{\Gamma}(\dot{\mathbf{x}}_{rk})(\vartheta_k - \mathbf{\Omega}_k \hat{\varphi}_k) \}^T \Delta\xi_k \right] \\ &\quad - \sum_{k=1}^n \left[k_q \left[n_k \Delta\xi_k + \sum_{i=1}^{n_k} (\alpha\eta_{ki} + \gamma\rho_{ki}) \right]^T \mathbf{S}^{-1} \mathbf{\Omega}_k \mathbf{S}^{-T} \Delta\xi_k \right] \\ &\quad - \sum_{k=1}^n \left[(\vartheta_k - \mathbf{\Omega}_k \hat{\varphi}_k)^T \mathbf{L}_k^{-1} \dot{\varphi}_k \right] \\ &\quad - \mathbf{s}^T (\mathbf{B} + \mathbf{K}_s) \mathbf{s} - \mathbf{s}^T \mathbf{\Gamma}_z(\dot{\mathbf{z}}_r, \ddot{\mathbf{z}}_r) \Delta\theta_z - \dot{\theta}_z^T \mathbf{L}_s^{-1} \Delta\theta_z \\ &= - \sum_{k=1}^n \left[k_q \left[n_k \Delta\xi_k + \sum_{i=1}^{n_k} (\alpha\eta_{ki} + \gamma\rho_{ki}) \right]^T \Lambda_k \Delta\xi_k \right] \\ &\quad - \mathbf{s}^T (\mathbf{B} + \mathbf{K}_s) \mathbf{s}, \end{aligned} \quad (52)$$

where $\Lambda_k = \mathbf{S}^{-1} \mathbf{\Omega}_k \mathbf{S}^{-T}$ are positive definite matrices.

Since $\eta_{kikj} = -\eta_{kjk i}$, and by choosing $\lambda_{kikj} = \lambda_{kjk i}$, we have

$$\sum_{i=1}^{n_k} \eta_{ki} = 0. \quad (53)$$

To ensure the stability, the adaptive interaction forces, $\Delta\rho_{ki}$ are defined such that:

$$\sum_{k=1}^n \sum_{i=1}^{n_k} k_q \gamma \Delta\xi_k^T \Lambda_k \Delta\rho_{ki} = 0. \quad (54)$$

Substituting (29) into (54), and simplifying, we obtain:

$$(\Delta\xi_k^T \Lambda_k - \Delta\xi_k^T \Lambda_{\bar{k}}) \Re(\theta_{k i \bar{k} i}) \Delta\psi_{k i \bar{k} i} = 0. \quad (55)$$

Using (30), it can be shown that the equation (55) holds if the rotational angle $\theta_{k i \bar{k} i}$ is defined as follows:

$$\theta_{k i \bar{k} i} = \tan^{-1} \left\{ \frac{(\Delta\xi_k^T \Lambda_k - \Delta\xi_k^T \Lambda_{\bar{k}}) \Delta\rho_{k i \bar{k} i}}{(\Delta\xi_k^T \Lambda_k - \Delta\xi_k^T \Lambda_{\bar{k}}) \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \Delta\rho_{k i \bar{k} i}} \right\}. \quad (56)$$

For the case that $\Delta\xi_k^T \Lambda_k - \Delta\xi_k^T \Lambda_{\bar{k}} = 0$, no update for the rotational angle is required since (55) is satisfied with any $\Re(\theta_{k i \bar{k} i})$; thus previous value of $\theta_{k i \bar{k} i}$ can be used. Therefore, $\Re(\theta_{k i \bar{k} i})$ can always be defined. Hence, (52) can be simplified as:

$$\dot{V} = - \sum_{k=1}^n n_k k_q \Delta\xi_k^T \Lambda_k \Delta\xi_k - \mathbf{s}^T (\mathbf{B} + \mathbf{K}_s) \mathbf{s} \leq 0. \quad (57)$$

We are now able to state the following theorem:

Theorem. The control inputs for the laser-driven system given by (36) and (37) together with the control input for the robot-assisted stage given by (42) and (43) guarantees the stability of the closed-loop control system for coordinative and simultaneous manipulation of multiple microscopic objects. The convergence of $\Delta\xi_k \rightarrow \mathbf{0}$, $k = 1, 2, \dots, n$, and $\mathbf{s} \rightarrow \mathbf{0}$ as $t \rightarrow \infty$ ensure the completeness of the control objectives of: (i.) individual and coordinative manipulation of the target micro-objects using micro-hands with multiple laser-driven fingertips, and (ii.) group transportation of all the grasped target objects by maneuvering the robot-assisted stage.

Proof. From (49), (50) and (57), V is non-negative and $\dot{V}$ is negative definite in $\Delta\xi_k$ and $\mathbf{s}$, hence V is bounded. Therefore, we can conclude about the boundedness of Q_k , $\mathbf{s}$, $\dot{\varphi}_k$, and $\Delta\theta_z$. From (14), $h_l(\Delta\mathbf{X}_k)$ is bounded. Therefore $\mathbf{x}_k$ is bounded if $\mathbf{x}_0$ is bounded. Thus, $\frac{\partial h_l(\Delta\mathbf{X}_k)}{\partial(\Delta\mathbf{X}_k)}$ is bounded. Therefore, from (15), $\Delta\xi_k$ is bounded.

From (34), $\dot{\mathbf{x}}_{rk}$ is bounded if $\mathbf{x}_0$ is bounded. Using (53), and property (1), we can conclude about the boundedness of $\Delta\dot{\mathbf{X}}_k$ from the closed-loop equation in (46). Thus, from (15), $\Delta\dot{\xi}_k$ is bounded. Also from (47), we have that $\dot{\mathbf{s}}$ is bounded. Therefore, the boundedness of $\dot{V}$ is guaranteed. So, $\dot{V}$ is uniformly continuous. Applying Barbalat's lemma [32], we have $\dot{V} \rightarrow 0$ as $t \rightarrow \infty$ which also indicates that $\Delta\xi_k \rightarrow \mathbf{0}$, $k = 1, 2, \dots, n$, and $\mathbf{s} \rightarrow \mathbf{0}$ as $t \rightarrow \infty$.

Remark 1. In this paper, the grasping formations including the target micro-objects and the corresponding laser-driven fingertips are considered as rigid bodies during manipulation and the flexibility or deformability of the target micro-objects are not considered. Since the position feedback errors of the target objects are obtained in image space, the system should be robust to modeling uncertainty [35] including the deformability of the micro-objects. Future research work would be devoted to the robustness analysis of the proposed manipulation system using multiple laser-driven fingertips, in presence of flexibility of micro-objects or cells.

Remark 2. In this paper, the local control objective is to manipulate multiple target micro-objects towards a desired region. The proposed control technique in this paper can also be utilized to manipulate multiple target micro-objects to follow independent trajectories. In that case, multiple independent regions whose positions and sizes are variable are defined. It is noted that when the desired regions are defined to be arbitrary small, the control problem reduces to traditional tracking control of the target micro-objects. The control forces which are

proportional to the region errors (15) of the target micro-objects thus drive the target objects towards the corresponding desired regions or trajectories. Concurrently, the adaptive forces (29) are employed for collisions avoidance between the micro-hands during the course of manipulation.

Discussion. This paper presents a robotic control technique for cooperative and mobile manipulation of microscopic objects which can be of arbitrary types in the micro-world by using laser-driven fingertips and robot-assisted stage control. The target micro-objects to be manipulated can even be untrappable micro-objects such as metallic micro-wires or opaque objects, relatively large micro-objects, and laser-sensitive biological cells. The proposed control technique is then possibly applicable, for example, in the processes of integrated circuit fabrication or micro-fabrication [36], in which micro-chips or micro-devices can be grasped and manipulated by using micro-hands with multiple laser-driven fingertips and robot-assisted stage control.

In biological applications and clinical diagnosis, direct trapping and manipulation of cells using laser tweezers may cause photo-damage to the cells due to several reasons: (i) two-photon absorption [37], (ii) transient local heating [38], and (iii) creation of reactive chemical species due to photochemical processes [39]. This paper provides a robotic control technique for cell manipulation using grasping formations of micro-hands with multiple laser-driven fingertips and robot-assisted stage control; and therefore, it can be employed for various biological applications, regardless of cell species or intended manipulation time. Also, without the demands of specific types of the liquid medium or any fabricated micro-tools, the proposed control technique is promisingly applicable in in-vivo cell manipulation [40]. In the in-vivo applications, several cells can be first trapped and then utilized as laser-driven fingertips to grasp the cells of interests. The target cells can thus be manipulated by cooperative control of the laser-driven fingertips and/or the whole body, and thus preventing the target cells from photo-damages.

In manipulation of micro-objects or cells with irregular shapes, however, the grasping points of the laser-driven fingertips on the target micro-objects or cells need to be determined such that the grasping formations of the fingertips and the target objects remain stable during manipulation. Besides, the manipulation speed of the target micro-objects or cells should also be restrained to keep the grasping formation balanced during manipulation. A saturation controller [41] can be implemented to maintain the manipulation speeds of the micro-hands and the robot-assisted stage.

4 EXPERIMENT

The E3500 series optical tweezers system at Nanyang Technological University, Singapore was utilized for implementation of the proposed control technique. The main setup consists of a robot-assisted stage (Marzhauser Wetzlar, SCAN IM) which can be operated in a 2-D space with the resolution of $0.01\mu\text{m}$ and the range of $120\text{mm} \times 100\text{mm}$. With the aid of an multiple optical trap device (Elliot Scientific), the optical tweezers system is able to generate and manipulate multiple laser traps individually and simultaneously with the near-infrared wavelength of 1070nm and the resolution of $16\mu\text{m}$. Two digital cameras (Basler pi640-210gm and Teledyne Dalas GM00-H6400) were employed for measuring the positions of the laser-driven fingertips and the target micro-objects, and the encoders which are mounted on the robot-assisted stage were utilized for determination of the positions of the laser traps. A Plan Apo VC 100X Oil objective lens with $\text{NA}=1.4$ was used for observing the workspace which is a micro-environment with dimensions of $47.95\mu\text{m} \times 36.11\mu\text{m}$. Fig. 11 illustrates an exemplification of the optical tweezers system. The proposed controllers were implemented using National Instruments LabVIEW, and the control inputs were generated to simultaneously control both the laser-driven system and the robot-assisted stage.

In the experiments, $5\mu\text{m}$ diameter latex micro-beads (with a refractive index of 1.60, and a density of $1500\text{kg}/\text{m}^3$) were trapped and utilized as laser-driven fingertips to grasp and manipulate the target objects, which were the cornflour particles. As the cornflour particles are inert due to its large sizes, it is difficult to trap and manipulate them directly by using individual laser beams.

In the first experiment, cooperative control of two micro-hands and the robot-assisted stage were utilized for coor-

Fig. 11. An exemplification of the optical tweezers system at Nanyang Technological University, Singapore. The main setup consists of an optical trap device, a microscope, a robot-assisted stage, and two cameras.

dinative and simultaneous manipulation of two cornflour particles with approximate diameters of $8\mu\text{m}$. Without losing generality of the proposed control technique, only the case of manipulation of two cornflour particles is considered in this experiment due to the limited field of view of the camera. Each cornflour particle was first grasped by a multi-fingered micro-hand, then two grasped cornflour particles were coordinatively manipulated to a desired region, which was specified as follows:

$$h(\Delta\mathbf{X}_k) = \Delta X_{k1}^2 + \Delta X_{k2}^2 - R^2 \leq 0, \quad (58)$$

and at the same time, all the grasped cornflour particles are transported as a group while the robot-assisted stage is maneuvered to follow a desired trajectory of the form: $z_1 = 15.8\mu\text{m} + 8.695\cos(0.4t)\mu\text{m}$; $z_2 = 24.3\mu\text{m} + 8.695\sin(0.4t)\mu\text{m}$. The control parameters for the laser-driven system and the robot-assisted stage were set as $k_q = 5 \times 10^{-4}$, $\mathbf{L}_k = 10^{-5}\mathbf{I}_2$, $\beta = 4$, $\chi = 2$, $R = 10.5\mu\text{m}$, $s_x(t) = s_y(t) = 1$, $r = 3.25\mu\text{m}$, $\sigma = 1$, $\mathbf{K}_s = 0.5\mathbf{I}_2$, $\mathbf{L}_s = 10^{-5}\mathbf{I}_4$, and the power of each laser trap was set at 0.1W . The region errors of the target objects which are defined as $\sqrt{\Delta\xi_{k1}^2 + \Delta\xi_{k2}^2}$ are shown in Fig. 12(a), while motion path of the robot-assisted stage and its tracking error are illustrated in Fig. 12(b) and Fig. 12(c), respectively. The snapshots at different time instants of the control system is shown in Fig. 13.

Bringing cells or micro-objects into contact is a mandatory step in many biological applications, including the studies of cell-cell interactions, cell adhesion, cell fusion, etc.. In the second experiment, two grasped target objects which were cornflour particles were brought into contact with each other while being manipulated to a desired scaling region. The grasped cornflour particles were rotated concurrently by rotating the multi-fingered micro-hands with the use of the rotational controller [20], while being driven into the desired region which was scaling down by the scaling factors (13):

$$s_x(t) = s_y(t) = \begin{cases} \frac{7R}{6} & t \leq 3 \\ \frac{7R}{6} + \frac{2R(t-3)^3}{375} - \frac{R(t-3)^2}{25} & 3 < t < 8 \\ \frac{5R}{6} & t \geq 8 \end{cases} \quad (59)$$

so that the grasped target objects are in contact with each other. The powers of the laser traps and the control parameters were set as in the first experiment, except for $r = 2.5\mu\text{m}$. The region errors of the target micro-objects is shown in Fig. 14, and the snapshots at different time instants of the control system are shown in Fig. 15.

In order to meliorate the process of bringing the target cells or micro-objects into contact, the repositioning of the fingertips was utilized in the third experiment. In this experiment, the fingertips that may block the contact points of the target objects are removed from

Fig. 12. Experiment 1. (a) Region errors of the target objects. (b) Motion path of the robot-assisted stage. (c) Tracking errors of the robot-assisted stage.

Fig. 13. Experiment 1: Snapshots at different time instants of the control system. (a) Initial position. (b) The target objects are being driven to a desired region. (c) The micro-hands are slightly rotated automatically to avoid collisions between the fingertips. (d) All the target objects are inside the desired region.

Fig. 14. Experiment 2. Region errors of the target objects.

the grasping formations so that the target objects can be brought into contact effectively. The control parameters for the laser-driven system and the powers of the laser traps were set as in the second experiment. After the two cornflour particles are brought into contact with each other, they were considered as a ‘single’ target object which is grasped by a single micro-hand with all the laser-driven fingertips. This ‘single’ target object was then rotated by rotating the micro-hand, and finally, it was transported to a desired position by maneuvering the robot-assisted stage while fixing the laser-driven fingertips. The initial and desired positions of the robot-assisted stage were $\mathbf{z}_0 = (7.4\mu\text{m}, 40.2\mu\text{m})^T$ and $\mathbf{z}_d = (21.7\mu\text{m}, 19.9\mu\text{m})^T$, respectively. The control parameters for the robot-assisted stage were $\sigma = 1$,

Fig. 15. Experiment 2: Snapshots of the control system at different time instants. (a) Initial position. (b) The target objects are being driven to a desired region. (c) The desired region is scaling down so that the target objects are brought into contact with each other. (d) The target objects are in contact with each other.

Fig. 16. Experiment 3. (a) Region errors of the target objects. (b) Motion path of the robot-assisted stage. (c) Regulation errors of the robot-assisted stage.

Fig. 17. Experiment 3: Snapshots at different time instants of the control system. (a) Initial position. (b) The desired region starts to scale down. (c) The two fingertips that block the contact points of the target objects are removed from the formations. (d) The target objects are in contact with each other. (e)-(f) After being in contact with each other, the formation of the two target objects are rotated about the center of the formation. (f)-(h) The formation of the two grasped target objects are manipulated as a whole while the stage is maneuvered to a desired position.

$\mathbf{K}_s = 7.5 \times 10^{-2} \mathbf{I}_2$, $\mathbf{L}_s = 10^{-5} \mathbf{I}_4$. The region errors of the target micro-objects are shown in Fig. 16(a), and the motion path of the robot-assisted stage and its position errors are shown in Fig. 16(b) and Fig. 16(c), respectively. The snapshots of the control system at different time instants are shown in Fig. 17.

5 Conclusion

In this paper, a novel cooperative control technique has been proposed for optical manipulation of multiple microscopical objects using robotic tweezers. In the proposed technique, several target micro-objects are coordinatively and simultaneously manipulated by cooperation control of micro-hands and robot-assisted stage. Several virtual micro-hands which are formed by coordinating multiple laser-driven fingertips are employed for indi-

vidual and dexterous manipulation of the grasped target objects, while robot-assisted stage control is utilized for global manipulation of all the target micro-objects. While current control techniques for optical tweezing are mostly dependent on the physical properties of the manipulated objects, this paper has presented for the first time a cooperative and mobile manipulation technique for multiple micro-objects based on multiple micro-hands and robot-assisted stage control, and thus bring robotic micro-manipulation closer to robotic manipulators in the physical world. A primary study on repositioning of the laser-driven fingertips has also been presented to allow the fingertips in the grasping formation to be repositioned. Rigorous mathematical formulation and stability analysis have been derived for achieving the control algorithm, and experimental results have been presented to illustrate the feasibility and effectiveness of the proposed control technique.

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