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RESEARCH ARTICLE

Laser-Actuated Multi-Fingered Hand for Dexterous Manipulation of Micro-Objects

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ABSTRACT Dexterous robotic manipulation refers to the coordination of multiple fingers or manipulators to grasp and manipulate a target object. In past decades, various achievements have been established in dexterous robotic manipulation in the physical world. However, such dexterous ability is rarely found in nano/micro manipulation, which is mainly due to the difficulty in developing actuators and sensors at a nano/micro-scale, as well as the dependence on the physical properties of objects. As a result, only limited and relatively simple micro-manipulation tasks such as pushing and picking have been realized so far. Here, we demonstrate a platform to achieve dexterous manipulation in the micro-world by developing a micro multi-fingered hand that is actuated by optical traps. The system consists of several micro laser-actuated fingers which are coordinated to function as a robotic micro-hand. Each micro-finger is configured with three degrees of freedom in a 2-dimensional space, and a system composed of coordinated micro-fingers can then be utilized for grasping, rotating, moving, and even levering and rolling of objects in micron scale. Thus, the proposed approach in this paper establishes a foundation in achieving dexterous robotic manipulation of objects at micron scale through the coordination of multiple micro-fingers.

INDEX TERMS Dexterous manipulation, laser-actuated micro-hand, micro-manipulation.

I. INTRODUCTION

Human hands are proficient at performing various manipulation tasks or activities by coordination of multiple fingers for holding, rotating, rolling, and moving objects. Recent advances in robotics and automation have laid the foundations to reproduce certain human skills in a robotic manipulation system, with the development of multi-fingered robot hands [1], [2], [3]. The progress achieved at a macro scale has also boosted the development of various micromanipulation systems. However, significant gap still exists when it comes to achieving such dexterity at micron scale as micro manipulations naturally diverge from conventional robotic manipulation.

Micro-manipulation refers to the manipulation of biological cells and inanimate micro/nano-sized objects. It has a wide range of applications in the research and development of micro technologies, biological and pharmaceutical science, and clinical diagnosis [4], [5], [6], [7]. However, due to the limitations in sensing and actuation at micron scale, it is difficult to develop a micro-hand that is similar to a multi-fingered robot hand in the physical world. Therefore, unlike a human hand which can manipulate any object easily and skillfully, current micro-manipulators can only be used for very simple and limited manipulation tasks.

Due to the limited controllable degrees of freedom (DoF), current micro-manipulators can only be used for simple manipulation tasks such as picking, pushing, and stretching [8], [9], [10], [11], [12], or the micro end-effectors or grippers have to be designed for grasping of micro-objects at a larger scale [13]. The feasibility and effectiveness of

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existing micro-manipulation systems are also highly contingent on the physical properties and dimensions of objects. The applications of a given micro-manipulation system are therefore limited to a few types of objects made of specific materials. For example, optical tweezers [14], [15], [16], [17] are capable of manipulating nano and micro-objects precisely with the usage of focused laser beams, but it is invalid for the manipulation of opaque objects, or biological cells which are too sensitive to light. Another example is a magnetic tweezers system, which is only applicable for manipulating ferromagnetic micro-objects [18], [19] which are typically larger in hundreds of microns. Several works have been carried out for the magnetic and optical manipulation of various objects [20], [21], [22], [23], [24], but together with existing micro-manipulators, they lack the flexibility of spatial resolution needed to achieve dexterous micro-manipulation. Thus, there is currently no common technique that can perform the dexterous manipulation of objects at micron scale for arbitrary materials, which can function as a similar role to the multi-fingered robot hand.

To achieve dexterous manipulation at micron scale, we develop a reconfigurable optically actuated robotic micro-hand in this work. A new multi-fingered manipulation system, consisting of several micro-fingers driven by multiple laser beams, is developed. The laser-actuated micro-fingers are coordinated to function as a micro multi-fingered hand to achieve various manipulation tasks in the micro-world. Each laser-actuated finger has three degrees of freedom (DoF) in a 2-dimensional space, and a system with reconfigurable and coordinated micro-fingers is thus able to perform dexterous micro-manipulation tasks by exploring the high DoFs of multiple micro-fingers, including grasping, rotating, and even rolling of micro-objects. The reconfigurable structure is also beyond the fixed configuration of macro robot hands, which provides more flexibility in manipulation tasks. Therefore, this work significantly contributes to achieving dexterous manipulation at micron scale.

II. DEXTEROUS MICRO ROBOT HAND

A. OVERVIEW AND CONCEPT

The basic component of our technique is the laser-actuated micro-fingers (see Figure 1). Each micro-finger has an elongated and transparent body and is optically trapped and driven by using two laser beams. When a highly focused laser beam passes through a portion of a micro-finger immersed in a medium, the generated trapping force holds the micro-finger near the beam's center. After each micro-finger is trapped, it can then be manipulated by the laser beams, which can thus be treated as micro-scale actuators under such formulation. The two lasers are spaced apart from one another along the length of each micro-finger. Therefore, the two optical traps function as the actuators of each finger. Both the planar and angular positions of the fingers can then be controlled simultaneously by moving and coordinating the laser beams. Either the finger-ends or any point along the length of the fingers can be used as contact points with target cells or objects for manipulation. Such a design has two advantages. First, each finger has three controllable DoFs, laying the foundation for dexterous micromanipulation tasks. Second, the fingers can be reconfigured online to suit various tasks by simply adding or removing laser traps.

The micro-fingers can be collected though manufacturing or fabrication [25], [26], or literally chosen as arbitrarily elongated living cells or micro-particles from nature, as long as they are optically trappable. Therefore, it also enhances the impact by broadening the feasible applications of the proposed technique. In this work, we selected two kinds of micro-fingers: micro-rods made of glass fiber, and rod-shaped cells called S-pombe yeasts. The micro-rods are commercially available or can be fabricated, while S-pombe yeasts can be cultured by a simple methodology.

Remark 1: In the proposed micro-manipulation system, laser-actuated micro-fingers are coordinated to achieve dexterous manipulation of objects in micron scale. Each micro-finger has an elongated and transparent body such that it can be optically trapped and driven by using two laser beams. However, there is no specific requirement on the properties of the objects being manipulated as long as it can be grasped by the micro-fingers. By coordination of multiple micro-fingers, the proposed micro-manipulation system thus functions as a similar role to the physical multi-fingered robot hand in manipulation of arbitrary objects.

B. MODELLING AND CONTROL

A system of several coordinated micro-fingers can then be used to grasp and manipulate micro-sized objects (see Figure 2). The control algorithm for each micro-finger driven by a pair of laser beams is derived based on its dynamic model. The dynamics of a laser-actuated finger is described using the Langevin equation as:

$$\boldsymbol{\gamma}_{drag} + \boldsymbol{\tau}_{opt} + \boldsymbol{f}_{Brn} = \mathbf{0}. \tag{1}$$

Equation (1) describes the balance of forces and moments acting on each micro-finger. It captures the relationship between the viscous or drag forces and moments $\boldsymbol{\gamma}_{drag}$, the forces and moments from the optical traps $\boldsymbol{\tau}_{opt}$ and the random Brownian motion $\boldsymbol{f}_{Brn}$. It is noted that in micro-manipulation, inertial forces are dominated by viscous forces due to the low Reynolds number.

To design a controller to manipulate the micro-finger, a coordinate system is chosen to be associated with the working space (see Fig. 1D). The translational and rotational velocities of the micro-finger is denoted as a column vector $\dot{\boldsymbol{z}} = (\dot{\boldsymbol{q}}, \dot{\theta})^T \in \mathcal{R}^3$, in which $\boldsymbol{q} = (q_1, q_2)^T \in \mathcal{R}^2$ and θ are respectively the planar and angular positions of the micro-finger. The viscous forces and moments $\boldsymbol{\gamma}_{drag} = -\boldsymbol{B}\dot{\boldsymbol{z}}$ tend to oppose the translational and rotational movements of the micro-finger, in which the matrix $\boldsymbol{B} \in \mathcal{R}^{(3\times3)}$ denotes the translational and rotational drag coefficients. The Brownian forces and moment $\boldsymbol{f}_{Brn}$ can be modeled as $\boldsymbol{f}_{Brn} = \boldsymbol{D}\boldsymbol{\xi}$ with $\boldsymbol{D} \in \mathcal{R}^{(3\times3)}$ being a matrix of constant parameters, and

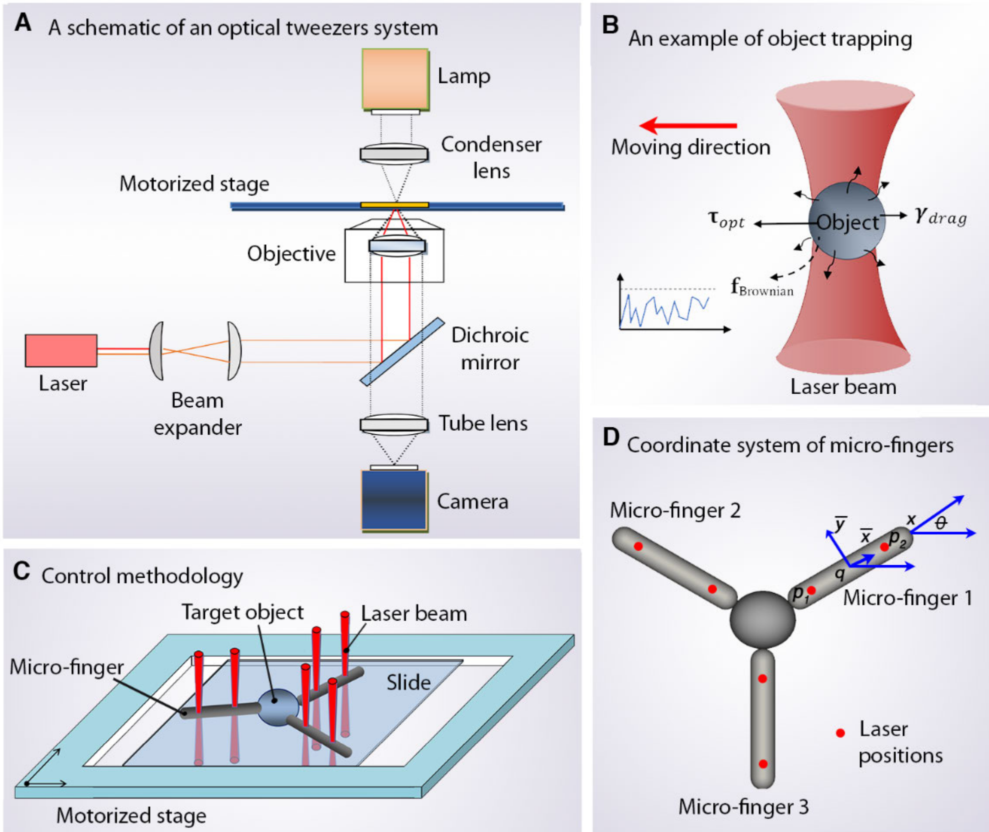

FIGURE 1. Concept and overview. The micro multi-fingered manipulation system is constituted by several micro-fingers and multiple laser beams. (A) A schematic of an Optical Tweezer System. (B) An illustration of optical trapping of a micro-object. (C) Multiple laser beams are generated to trap the fingers. Two laser beams are used to trap and drive each finger so that both the planar position and orientation of the micro-finger can be controlled simultaneously. (D) Coordinate system of the micro-fingers.

$\boldsymbol{\xi} \in \mathcal{R}^3$ representing a column vector of Gaussian white noises.

The term $\boldsymbol{\tau}_{opt} \in \mathcal{R}^3$ is a column vector of trapping forces and moments, which is $\boldsymbol{\tau}_{opt} = (\boldsymbol{\tau}_{trp}, \boldsymbol{\tau}_{mmt})^T$. The trapping forces acting on the micro-finger from the two laser beams are specified as

$$\boldsymbol{\tau}_{trp} = \boldsymbol{K}_1 \Delta \boldsymbol{p}_1 + \boldsymbol{K}_2 \Delta \boldsymbol{p}_2 \tag{2}$$

with $\Delta \boldsymbol{p}_1$ and $\Delta \boldsymbol{p}_2$ being the displacements between the lasers' positions $\boldsymbol{p}_1 = (p_{11}, p_{12})^T$, $\boldsymbol{p}_2 = (p_{21}, p_{22})^T$ and the laser-receiving portions -which are inside the trapping regions of the lasers- of the micro-finger. The matrices $\boldsymbol{K}_i$ with $i = 1, 2$ are the stiffnesses of the trapping forces, which can be achieved by transforming the matrices of trapping stiffnesses in the finger's coordinate frame, $\boldsymbol{\Gamma}_i$, into the coordinate system. That is, $\boldsymbol{K}_i = \boldsymbol{\Gamma}_i \boldsymbol{R}$ for $i = 1, 2$, where $\boldsymbol{\Gamma}_i = diag(\Gamma_{\bar{x}i}, \Gamma_{\bar{y}i})$ with $\Gamma_{\bar{x}i}$ and $\Gamma_{\bar{x}i}$ being the trapping stiffnesses along the latitudinal and longitudinal directions of the micro-finger, and $\boldsymbol{R}$ is a transformation matrix. The trapping moments of the two laser beams on the micro-finger are then specified as

$$\boldsymbol{\tau}_{mmt} = \|(\boldsymbol{p}_1 - \boldsymbol{q}) \times (\boldsymbol{K}_1 \Delta \boldsymbol{p}_1) + (\boldsymbol{p}_2 - \boldsymbol{q}) \times (\boldsymbol{K}_2 \Delta \boldsymbol{p}_2)\|. \tag{3}$$

Using equations (2) and (3), we can now rewrite the trapping forces and moments of the two laser beams on each micro-finger as:

$$\boldsymbol{\tau}_{opt} = \boldsymbol{K} \begin{bmatrix} \Delta \boldsymbol{p}_1 \\ \Delta \boldsymbol{p}_2 \end{bmatrix} \tag{4}$$

where

$$\boldsymbol{K} = \begin{bmatrix} \boldsymbol{K}_1 & \boldsymbol{K}_2 \\ s_1 \boldsymbol{K}_1 & s_2 \boldsymbol{K}_2 \end{bmatrix}$$

and

$$s_1 = \left[-(p_{12} - q_2) \;\; (p_{11} - q_1)\right],$$
$$s_2 = \left[-(p_{22} - q_2) \;\; (p_{21} - q_1)\right].$$

From (4), (1) can be rewritten as

$$\boldsymbol{B}\dot{\boldsymbol{z}} = \boldsymbol{K} \begin{bmatrix} \Delta \boldsymbol{p}_1 \\ \Delta \boldsymbol{p}_2 \end{bmatrix} + \boldsymbol{D}\boldsymbol{\xi}. \tag{5}$$

Next, we explore a Jacobian matrix describing the kinematics of a micro-finger. We denote $\boldsymbol{x}$ to be the planar position of a finger-end and d to be the distance between this finger-end to the center of the micro-finger. The relationships between the position of the micro-finger and its finger-end are

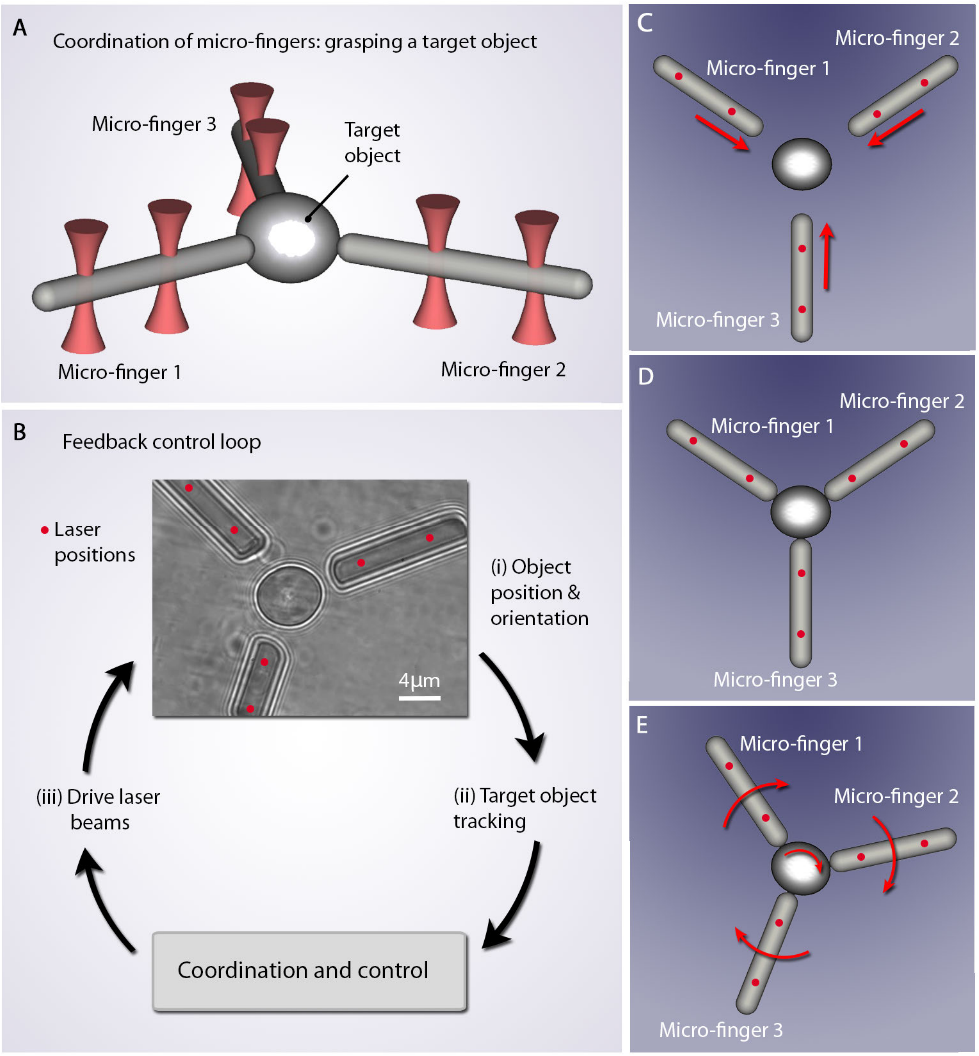

FIGURE 2. Coordination of multiple fingers. Several micro-fingers are coordinated to function as a micro multi-fingered hand to achieve dexterous manipulation tasks in the micro-world. (A) An illustration of the concept of multi-fingered manipulation where three micro-fingers are controlled to grasp a target object. (B) Key steps in a feedback control loop. Feedback errors of position and orientation of the target object are used in the control loop to enhance accuracy and improve robustness to modeling uncertainty. (C)-(E) An illustration of a multi-fingered hand performs a grasping and an in-hand manipulation task after it grasps a micro-object.

described as:

$$\boldsymbol{x} = \boldsymbol{q} + d \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}. \tag{6}$$

Differentiating (6) and rewriting to get:

$$\begin{bmatrix} \dot{\boldsymbol{x}} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} 1 & 0 & -d\sin\theta \\ 0 & 1 & d\cos\theta \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\boldsymbol{q}} \\ \dot{\theta} \end{bmatrix} \tag{7}$$

or

$$\dot{\boldsymbol{X}} = \boldsymbol{J}\dot{\boldsymbol{z}}, \tag{8}$$

with $\dot{\boldsymbol{X}} = \begin{bmatrix} \dot{\boldsymbol{x}} \\ \dot{\theta} \end{bmatrix}$ and $\boldsymbol{J} = \begin{bmatrix} 1 & 0 & -d\sin\theta \\ 0 & 1 & d\cos\theta \\ 0 & 0 & 1 \end{bmatrix}$ being the Jacobian matrix associated with the micro-finger.

In the proposed micro-manipulation system, each micro-finger is optically trapped and driven by using two laser beams. By controlling the positions of the two laser beams, both the position and orientation of the micro-finger can thus be controlled accordingly. Based on the dynamics in (5) and the Jacobian matrix $\boldsymbol{J}$, we can develop a feedback control algorithm for the variables $\Delta\boldsymbol{p}_1$ and $\Delta\boldsymbol{p}_2$ to manipulate the micro-finger as:

$$\begin{bmatrix} \Delta\boldsymbol{p}_1 \\ \Delta\boldsymbol{p}_2 \end{bmatrix} = -\boldsymbol{P}\boldsymbol{J}^{-1}\boldsymbol{K}_p(\Delta\dot{\boldsymbol{X}} + \alpha\Delta\boldsymbol{X}) \tag{9}$$

where $\boldsymbol{P} \in \mathcal{R}^{4\times 3}$ satisfies $\boldsymbol{KP} = \boldsymbol{I}_3$ with $\boldsymbol{I}_3$ being a 3×3 identity matrix, $\boldsymbol{K}_p$ is a gain matrix, α is a positive constant, and $\Delta\boldsymbol{X} = \boldsymbol{X} - \boldsymbol{X}_d$ with $\boldsymbol{X}_d = \begin{bmatrix} \boldsymbol{x}_d \\ \theta_d \end{bmatrix}$ being the desired planar and angular positions of the finger-end. In the controller (9), position and orientation errors of the micro-finger with respect to its desired pose, denoted as ΔX, and their derivatives are utilized in a feedback control algorithm for lasers' movement. With the usage of an inverse Jacobian matrix $\boldsymbol{J}^{-1}$ and a transformation matrix $\boldsymbol{P}$ specified in equations (8) and (9), respectively, these errors are transformed into $\Delta \boldsymbol{p}_1$ and $\Delta \boldsymbol{p}_2$ so as to control the movements of the lasers. As both the translational and orientation errors of the finger-end are utilized in the proposed feedback controller in (9), the robustness of the control scheme to modeling uncertainty is improved. The proposed feedback control scheme also enhances the robustness of the manipulation system in dealing with the uncertainty in the kinematics and dynamics of the laser-actuated micro-finger. The developed control algorithm is general and can be utilized for driving micro-fingers with different lengths and arbitrary laser receiving portions along the elongated body of the micro-finger.

By controlling and coordinating the positions and orientations of several laser-actuated micro-fingers, the micro multi-fingered hands can be configured for various tasks. The dynamics equation for the grasping formation of the micro-fingers and the target is described using the Langevin equation as:

$$\bar{\boldsymbol{\gamma}}_{drag} + \bar{\boldsymbol{\tau}}_{opt} + \bar{\boldsymbol{f}}_{Brn} = \boldsymbol{0}. \tag{10}$$

The term $\bar{\boldsymbol{\tau}}_{opt} \in \mathcal{R}^3$ is a column vector of total trapping forces and moments from all the micro-fingers, which is:

$$\bar{\boldsymbol{\tau}}_{opt} = (\sum_{i=1}^{n} \bar{\boldsymbol{\tau}}^i_{trp}, \sum_{i=1}^{n} \bar{\boldsymbol{\tau}}^i_{mmt})^T$$

with n being the number of micro-fingers.

Equation (10) describes the balance of forces and moments acting on the grasping formation of the micro-fingers and the target. These are the viscous or drag forces and moments $\bar{\boldsymbol{\gamma}}_{drag}$, the forces and moments from the optical traps that actuate the micro-fingers $\bar{\boldsymbol{\tau}}_{opt}$ and these from the random Brownian motion $\bar{\boldsymbol{f}}_{Brn}$. Here, we reduce the complexity of the model by considering the grasping formation as a whole body centered at the target object.

To develop a controller for feedback rotation and translation of a target, a coordinate system is chosen to be associated with the working space. The translational and rotational velocities of the target object is denoted as a column vector $\dot{\boldsymbol{y}} = (\dot{\boldsymbol{r}}, \dot{\varphi})^T \in \mathcal{R}^3$, in which $\boldsymbol{r} \in \mathcal{R}^2$ and φ are respectively the planar and angular positions of the target object. The viscous forces and moments $\bar{\boldsymbol{\gamma}}_{drag} = -\bar{\boldsymbol{B}}\dot{\boldsymbol{y}}$ tend to oppose the translational and rotational movements of the grasping formation, in which the diagonal matrix $\bar{\boldsymbol{B}} \in \mathcal{R}^{3\times3}$ denotes the translational and rotational drag coefficients. The Brownian forces and moment $\bar{\boldsymbol{f}}_{Brn}$ can be modeled as $\bar{\boldsymbol{f}}_{Brn} = \bar{\boldsymbol{D}}\bar{\boldsymbol{\xi}}$ with $\bar{\boldsymbol{D}} \in \mathcal{R}^{3\times3}$ being a matrix of constant parameters, and $\bar{\boldsymbol{\xi}} \in \mathcal{R}^3$ representing a column vector of Gaussian white noises.

The trapping forces acting on a micro-finger i from the two corresponding laser beams are specified as $\bar{\boldsymbol{\tau}}^i_{trp} = \boldsymbol{K}^i_1\Delta\boldsymbol{p}^i_1 + \boldsymbol{K}^i_2\Delta\boldsymbol{p}^i_2$ with $\Delta\boldsymbol{p}^i_1$ and $\Delta\boldsymbol{p}^i_2$ being the displacements between the lasers' positions $\boldsymbol{p}^i_1$, $\boldsymbol{p}^i_2$ and the corresponding laser-receiving portions of the micro-finger i, and $\boldsymbol{K}^i_1$ and $\boldsymbol{K}^i_2$ are the stiffnesses of the trapping forces. It is noted that the moments of trapping forces from the two laser beams on a micro-finger i is now used to rotate the target object instead of the micro-finger. That is:

$$\bar{\boldsymbol{\tau}}^i_{mmt} = \|(\boldsymbol{p}^i_1 - \boldsymbol{r}) \times (\boldsymbol{K}^i_1\Delta\boldsymbol{p}^i_1) + (\boldsymbol{p}^i_2 - \boldsymbol{r}) \times (\boldsymbol{K}^i_2\Delta\boldsymbol{p}^i_2)\|.$$

Using equations (2),and (3), we can now rewrite the trapping forces and moments of the laser beams on the micro-finger i as:

$$\bar{\boldsymbol{\tau}}^i_{opt} = \bar{\boldsymbol{K}}^i \begin{bmatrix} \Delta\boldsymbol{p}^i_1 \\ \Delta\boldsymbol{p}^i_2 \end{bmatrix} \tag{11}$$

where

$$\bar{\boldsymbol{K}}^i = \begin{bmatrix} \boldsymbol{K}^i_1 & \boldsymbol{K}^i_2 \\ \bar{s}^i_1\boldsymbol{K}^i_1 & \bar{s}^i_2\boldsymbol{K}^i_2 \end{bmatrix}$$

and

$$\bar{s}^i_1 = \left[-(p^i_{12} - r_2) \;\; (p^i_{11} - r_1)\right],$$
$$\bar{s}^i_2 = \left[-(p^i_{22} - r_2) \;\; (p^i_{21} - r_1)\right].$$

From (11), (10) can be rewritten as:

$$\bar{\boldsymbol{B}}\dot{\boldsymbol{y}} = \sum_{i=1}^{n} \bar{\boldsymbol{K}}^i \begin{bmatrix} \Delta\boldsymbol{p}^i_1 \\ \Delta\boldsymbol{p}^i_2 \end{bmatrix} + \bar{\boldsymbol{D}}\bar{\boldsymbol{\xi}}.$$

The controller for coordination of multiple micro laser-actuated fingers for feedback rotation and translation of a target object is proposed as:

$$\begin{bmatrix} \Delta\boldsymbol{p}^i_1 \\ \Delta\boldsymbol{p}^i_2 \end{bmatrix} = -\frac{1}{n}\bar{\boldsymbol{P}}^i\bar{\boldsymbol{K}}^i_p(\Delta\dot{\boldsymbol{y}} + \bar{\alpha}\Delta\boldsymbol{y}) \tag{12}$$

where $\bar{\boldsymbol{P}}^i \in \mathcal{R}^{4\times3}$ satisfy $\bar{\boldsymbol{K}}^i\bar{\boldsymbol{P}}^i = \boldsymbol{I}_3$ with $\boldsymbol{I}_3$ being a 3×3 identity matrix, $\bar{\boldsymbol{K}}^i_p$ are gain matrices, and $\bar{\alpha}$ is a positive constant. In the controller (12), $\Delta\boldsymbol{y} = \boldsymbol{y} - \boldsymbol{y}_d$ is the feedback error with $\boldsymbol{y}_d = \begin{bmatrix} \boldsymbol{r}_d \\ \varphi_d \end{bmatrix}$ being the desired planar and angular positions of the target object. It is noted that both the translational and orientation errors of the target object are utilized in the proposed feedback controller in (12) to improve the robustness to modeling uncertainty. The proposed feedback control scheme also enhances the robustness of the manipulation system in dealing with the uncertainty in the kinematics and dynamics of the grasping formation.

Remark 2: In order to perform manipulation tasks, the objective is to control the movement of the lasers so as to control the micro-fingers, and thus manipulate an object. In our approach, we use the feedback position and orientation errors of the object, denoted as $\Delta\boldsymbol{y}$, and their derivatives to coordinate the micro-fingers, as illustrated in equation (12). With the usage of the transformation matrices $\bar{\boldsymbol{P}}^i$ specified in equation (12), there errors are transformed into $\Delta\boldsymbol{p}^i_1$ and $\Delta\boldsymbol{p}^i_2$ so as to control the movements of the lasers.

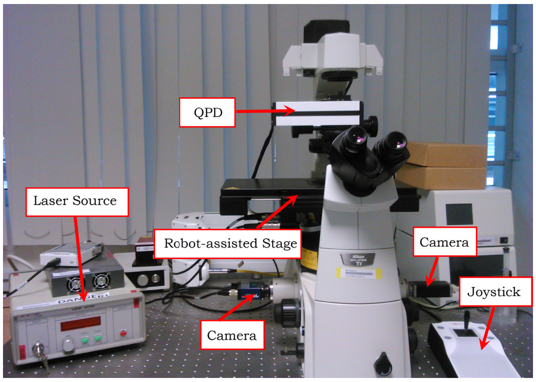

FIGURE 3. An optical tweezers system for object manipulation using a micro laser-actuated multi-fingered hand.

III. EXPERIMENTS

The proposed micro multi-fingered system are implemented and tested for various dexterous micro-manipulation tasks such as grasping, rotating, rolling and levering of micro-objects and experimental results are presented in this section.

A. MANIPULATION PLATFORM

Our platform for object manipulation using a micro laser-actuated multi-fingered hand is based on an optical tweezers system (Elliot) equipped with an inverted microscope (Nikon, Eclipse), as shown in Fig. 3. The system consists of a laser source (IPG Photonics, YLR 10-1070-LP) for generating of infrared laser beams with a wavelength of $1070nm$. A laser-steering system and an acousto-optic deflectors module (Elliot) are used to create and drive multiple optical traps simultaneously with a resolution of $16pm$. A camera system (Basler piA640-210gm: 648×488 pixels, 210 frames per second) together with an oil objective lens (Plan Apo VC $100X$) is employed for monitoring a manipulation space of $47.95\mu m$ in length and $36.11\mu m$ in width. A 2-D motorized stage (Marzhauser Wetzlar) operates with a resolution of $0.01\mu m$ in a space of $120mm$ in length and $100mm$ in width.

The positions and orientations of target objects and laser-actuated micro-fingers can be measured by using either the camera system associated with a video-based detection technique [27] or a custom-written LabVIEW program. Information on the positions and orientations of target objects and micro-fingers was input into a written LabVIEW program, and control signals were then generated for steering the positions of optical traps.

B. RESULTS

In the experiments, we used two types of micro-fingers to manipulate the target objects, which were micro-rods and S-pombe yeasts. These two types of micro-fingers are either commercially available or can be easily cultured. The micro-rods (Nippon Electric Glass) are manufactured by cutting glass fiber and have a broad available range of rod diameters ($1.5\mu m$ to $30\mu m$) and lengths ($5\mu m$ to $30\mu m$). We used normal length micro-rods with rod diameters of $4\mu m$ and a mean rod length of $15\mu m$ to $20\mu m$ to manipulate micro-sized objects.

Schizosaccharomyces pombe (S-pombe) is a rod-shaped yeast species with $2\mu m$ to $3\mu m$ in diameter and $7\mu m$ to $14\mu m$ in length [28]. One can also purchase them on the open market in frozen form. Once unfrozen, they can be cultured by putting them into different media [29]. We created a simple culture medium of yeast extract and glucose with concentrations of 10% in volume for each. The medium containing S-pombe yeasts was then placed in a dark location for 3 to 7 days, which allowed them to grow and reproduce. After this period, the amount of yeast became very large, and was ready for use in the experiments.

In this work, corn-flour particles, which can be bought easily at an open market, were chosen as target objects due to their wide range of sizes. Corn-flour particles together micro-fingers were first mixed in a tube with deionized/ultra-pure water (Bio-Rev), and then brought to a glass slide using a micro-pipette. Eventually, the sample was placed on the objective lens of the optical tweezers system for the experiments.

1) OBJECT MANIPULATION AND RECONFIGURATION

The proposed method is flexible, as any number of rod-shaped micro-objects that are trappable by laser beams can be used as fingers for the micro-hands. Figure 4A-4C show the processes of grasping target micro-objects by using two or three micro-fingers. The objects which are grasped can then be rotated and moved by coordination of the laser-actuated micro-fingers. The performances of the feedback control algorithm on rotation and movement of target objects by using two micro-fingers illustrated in Figure 4A are shown in Figure 4D. In Figure 4D, the horizontal axes show manipulation time and the vertical axes indicate the rotation or position errors in object manipulation. These errors are measured as the differences between the position and orientation of the object being manipulated with respect to its desired poses. The numerical results of the manipulation errors at different time instants are also shown in Table 1. We achieved a distance error in object manipulation of $0.11\mu m$ and a rotational error of $0.006rad$ after 5 seconds of the manipulation time.

By simply turning on or off the laser beam (i.e., the micro actuator), each micro-finger can be easily added into or removed from the overall hand. All the micro-fingers are mobile without physical constraints, such that the overall hand can be formulated as an arbitrary structure, by varying the relative posture between fingers. Those variations can be flexibly realized online, where no re-fabrication or re-construction is required. By using a micro multi-fingered hand, a grasped object can be rotated to an arbitrary angular position. However, translation of a grasped object by controlling a micro multi-fingered hand is limited within the field of view of the microscope. To overcome this limitation, stage control can be used for translation of a grasped object to

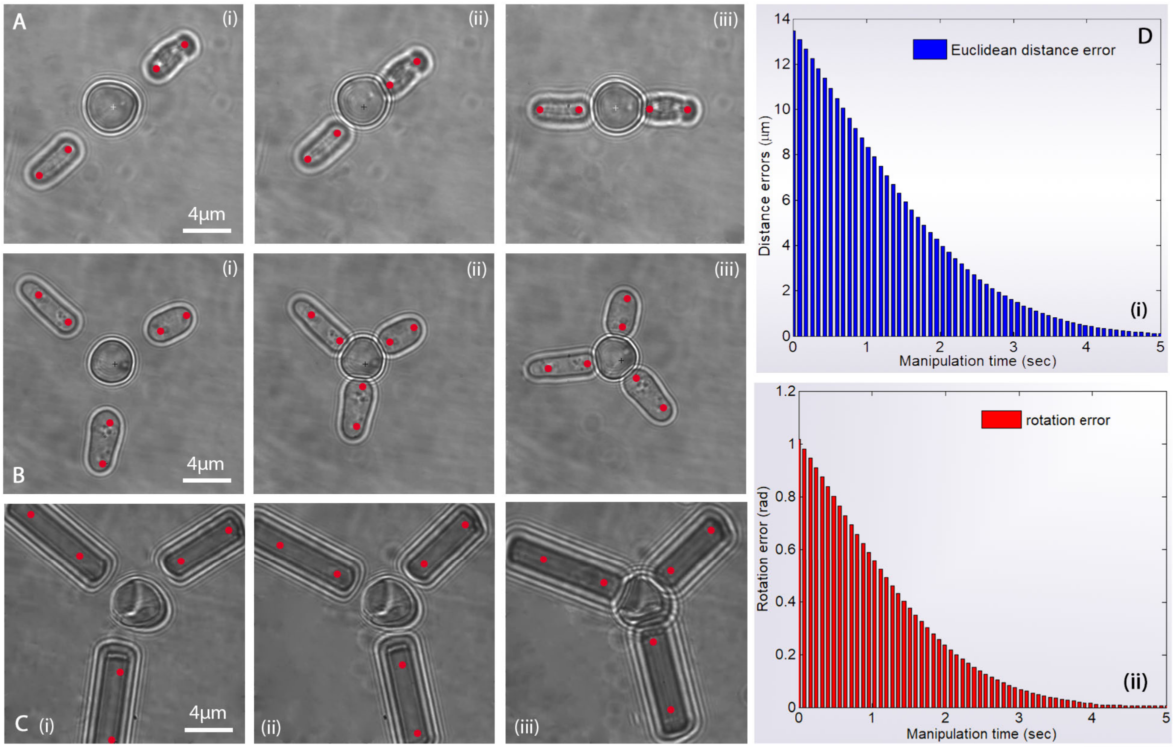

FIGURE 4. Experimental results on grasping of target micro-objects by using multiple micro-fingers. The proposed method is general in the sense that any rod-shaped micro-objects that are trappable can be used as fingers, and it also allows users to add more micro-fingers or remove redundant ones (A) Two S-pombe yeasts are trapped as the micro-fingers, which are then coordinated to grasp and rotate a target micro-object. (B) Three S-pombe yeasts are tapped to form a three-fingered micro-hand for grasping and manipulation tasks. (C) Three micro-rods are trapped as micro-fingers. (D) Positioning and rotation errors in manipulation of the target object by using two S-pombe yeasts in (A).

TABLE 1. Position and rotation errors at different time instants in object manipulation using two S-pombe yeasts (shown in Figure 4A).

Time (s) / Errors	0	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
Position error (μm)	13.50	10.90	8.32	5.94	3.98	2.50	1.62	0.91	0.48	0.24	0.11
Rotation error (rad)	1.020	0.803	0.556	0.376	0.236	0.139	0.068	0.034	0.016	0.007	0.006

a destination which is beyond the camera's field of view. A stage with 3 DoF can also be used to achieve position control in a 3-dimensional space.

The proposed micro-hand with the aforementioned features is beyond the conventional robot hands at a macro scale. Figure 5A-5D show the manipulation processes of different targets with different configurations of the micro-hands. In these grasping formations, the micro-fingers can contact the target objects either by their finger-ends, or by any point along their elongated bodies, or a mixture of both.

For a relatively smaller target object, a K grasping configuration can be set for grasping and transportation (see Figure 5B). Specifically, a finger-side is employed to push the micro-object while two finger-ends from the other two micro-fingers are used to stabilize the object in the grasping formation. In this grasping configuration, the average physical distance between the nearby laser beams and the object was recorded to be more than four times for the case where optically trapped particles [24] were used.

For a relatively large target object, a cage configuration can be formed instead (see Figure 5D). Moving by caging is desirable for those large targets, as it enhances the contact surfaces between the fingers and the target, guaranteeing a more stable grasp; such a cage can also be shaped as an arrow so as to reduce the drag force on the grasping configuration (see Figure 5C). The ability to be reconfigurable thus enhances the flexibility of the micro multi-fingered hand, and allows it to adapt to different tasks or requirements.

The aforementioned examples illustrate the reconfigurable capability of the developed micro-hand. Note that arbitrary grasping formations generated by the micro-hand can be realized with the proposed general feedback control algorithm. The performances of the feedback control algorithm on movement of target objects by using a caging formation as in

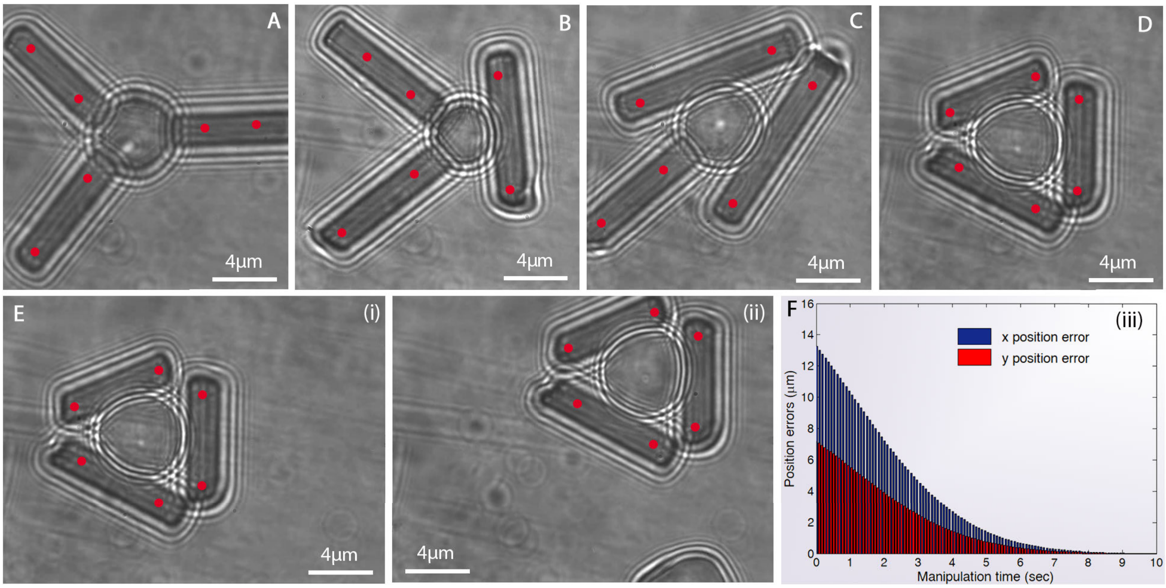

FIGURE 5. Grasping results using the reconfigurable multi-fingered hand. (A)-(D) Grasping and manipulation of target objects by three-fingered micro-hand based on different grasping configurations. (E) The configuration in (D) is used to grasp and manipulate the object to a desired position. (F) Position errors of the object manipulation task in (E).

TABLE 2. Position errors at different time instants in object manipulation using a caging formation (shown in Figure 5E).

Time (s) / Errors	0	1	2	3	4	5	6	7	8	9	10
x position error (μm)	13. 30	10.10	7.22	4.50	2.66	1.35	0.67	0.28	0.11	0.04	0.01
y position error (μm)	7.19	5.50	3.92	2.44	1.44	0.74	0.36	0.15	0.06	0.02	0.01

Figure 5E, are shown in Figure 5F and Table 2. The position errors in object manipulation were controlled to be less than 10*nm* in both axes after 10 seconds of the manipulation time. The high-accuracy positioning, and rotation ability is mainly due to the feedback controller and precise optical trapping used in this work, which further guarantees the realization of versatile in-hand tasks.

2) ROLLING OF OBJECT WITH MICRO ROBOT HAND

The proposed optically actuated micro-hand can be used to roll micro-objects, which is a useful motion to investigate the property of biological cells. Rolling adhesion, for example, a process in which cells passively roll along surfaces under shear flow, plays an important role in inflammatory responses and cancer metastasis [30]. Rolling adhesion is also used on vascular surfaces in recruiting platelets to specific organs or to sites of infection or injury [31], [32]. Furthermore, dexterous micro-manipulation, such as rolling, is required for rapid improvement in the manufacturing processes of many micro-scale mechanical systems, such as micro-electro-mechanical systems (MEMS).

However, because such a rolling motion incorporates both translational and rotational motion, it is difficult to replicate in vitro with existing micro-manipulators. Such dexterous motion for micro-objects can be realized with our developed micro robot hand. The back and forth rolling of a micro-object held between two micro-fingers (S-pombe yeast cells) is depicted in Figure 6. The motion of one micro-finger (the upper one in our case) was controlled to move horizontally while the other finger (lower) was kept stationary to support the object. This experiment was inspired by the pill rolling action, in which a person attempts to roll a pill or another small object between the thumb and index finger [33]. Similarly, in Figure 6, the moving (upper) S-pombe yeast cell acts like a micro-index finger, while the stationary (lower) S-pombe yeast cell acts like a micro-thumb. In the experiment, the target micro-object (corn flour particle) slipped across the surface of S-pombe yeast cells due to the low contact friction. To ensure a pure and smooth rolling motion, the micro-object was held in place by a laser beam that moved synchronously to a point on the rolling micro-object. This contact friction can be increased in the future by creating (or cutting) small grooves around the circumference of micro-rods.

The result obtained in this section thus demonstrates the feasibility of rolling an object in the micro-world, with the advantages of simple and easy implementation.

3) LEVERING A LARGE MICRO-OBJECT WITH A MICRO ROBOT HAND

As the trapping force of a laser beam is relatively smaller, it is usually difficult for optical tweezers to manipulate larger micro-objects. In this section, we show that the fingertip

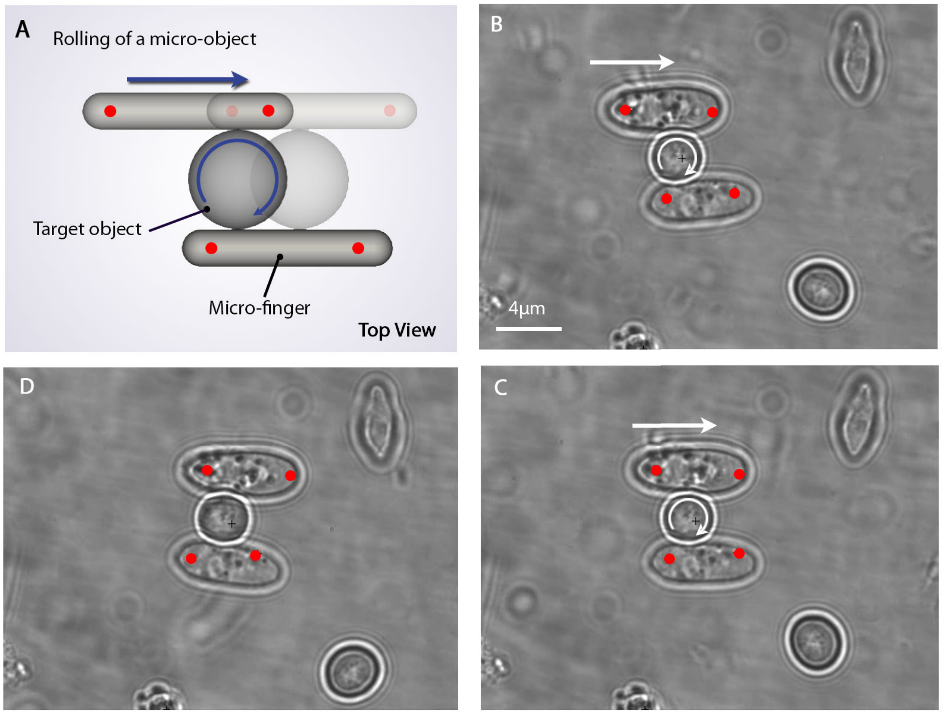

FIGURE 6. Rolling of a micro-object. Rolling of a target object in the micro-world can now be achieved by using a micro-hand with two coordinated micro-fingers. One micro-finger is kept stationary while the other is controlled to move in a reciprocating way to roll the target object on the surfaces of the micro-fingers.

force of a micro-finger can be amplified based on the lever principle. In the previous parts, each micro-finger was controlled by two laser beams. If we can fix one laser beam and move the other, the micro-finger can thus function as a lever which operates around the laser receiving portion of the fixed laser beam. However, since the trapping force that fixes the laser-receiving portion is also small, we must use a fulcrum instead.

When a micro laser-actuated finger is used as a lever, the applied trapping force is amplified based on the ratio of the distance from the effort to the fulcrum and the distance from the load to the fulcrum. The concept is validated in Figure 7, where a micro laser-actuated finger can be used to manipulate a larger target micro-object in a small distance. The load (target micro-particle) and effort (trapping force) are applied to either end of the micro-finger, which is a micro-rod. The micro-finger pivots around a central fulcrum which can be created at a desired location using a photo-resist anchored to a glass substrate.

IV. DISCUSSION

The current micro-manipulation techniques are either applicable to only a few specific types of micro-objects, or merely limited to several simple manipulation tasks. In this work, we have made an essential step towards achieving dexterous manipulation in micro-world. A new multi-fingered micro-manipulation system has been developed to demonstrate the feasibility of dexterous manipulation in the micro-world. In fact, this research has developed a new robotic hand in the micro world, which provides a more general solution to various micro manipulation tasks, in the sense that the dexterous manipulation techniques reported at a macro scale can also be migrated to the micro-world under such a framework.

The proposed micro laser-actuated multi-fingered hand enables one to perform dexterous manipulation tasks in the micro-world, including grasping, rotating, and even rolling of micro-objects. Each laser-powered finger has three degrees of freedom and can be simply configured with different formations to adapt to different targets or tasks. Due to the simplicity of design and operation for the proposed micro-finger, it can even be employed as a laser-actuated micro-lever without modification.

Research on the micro multi-fingered robotic hand is just the beginning. The proposed method has opened up several new possibilities in dexterous micro-manipulation. Future research will be devoted to exploring bi-manual manipulation by coordination between micro multi-fingered hands or the manipulation of heterogeneous multi-micro-agents, which has not been explored in micro-manipulation. The ability to coordinate multiple micro-hands or a combination of micro-hands and other micro-tools will benefit many in vitro applications, including cell-cell interactions [34], adhesive force measurement [35], micro-injection [36], etc. Additionally, we plan to use the system to develop a manipulation technique for micro thread-like structures. Specifically, we will use two micro-fingers to pick up a thread-like

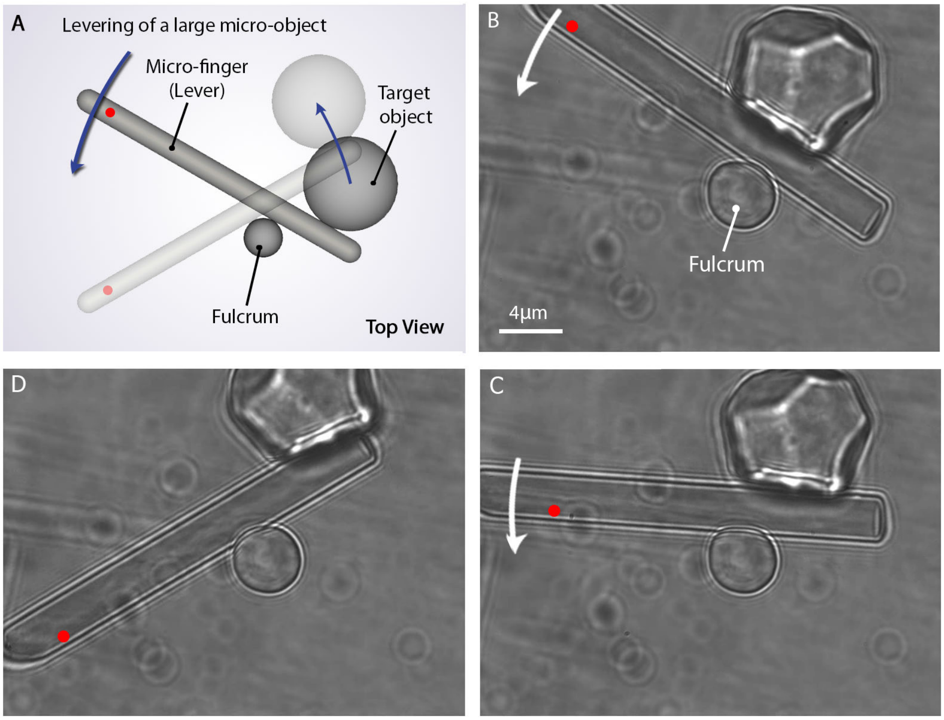

FIGURE 7. Levering of a large micro-object. The force exerted by the fingertip can be amplified under the level formulation with the aid of a stationary fulcrum and one laser beam. The amplifying ratio can also be adjusted by varying the distance between the laser beam and the fulcrum.

structure and make it oscillate, which would be useful in the study of the flagellum [37]. Moreover, focus can be directed towards the coordination of multiple micro-fingers for the lever-based manipulation of micro-objects. By coordinating multiple micro-fingers together with using more fulcrums, the levered micro-sized objects can then be manipulated in a larger distance in two dimensions.

Additionally, learning algorithms could be introduced such that the micro multi-fingered hands would act intelligently to more complex scenarios or tasks. Deep Neural Networks for perception and reinforcement learning for the motion planning of micro-fingers can also be explored, such that the micro robot hand can properly react to and deal with unexpected events, by training a series of deep networks with the data collected from real-world experiments.

V. CONCLUSION

To summarize, our work opens the door to the dexterous robotic manipulation of microscopic objects. We have demonstrated a variety of dexterous micro-manipulations using a simple micro multi-fingered hand that does not require any special fabrication machines. We believe that the scientific community will benefit from this research, as we now have a micro-manipulation tool that is easier to use.

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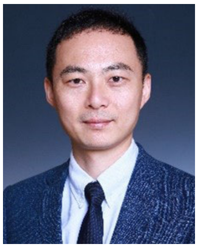

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