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Non-Contact Manipulation of Microbeads via Pushing and Pulling using Magnetically Controlled Clusters of Paramagnetic Microparticles

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Abstract*— In contact micromanipulation, the adhesive forces between manipulators and microobjects decrease the chances of achieving successful releases at the desired positions. We study a non-contact micromanipulation technique of microbeads (300 μm in average diameter) using clusters of paramagnetic microparticles (100 μm in average diameter). This non-contact micromanipulation is done using the hydrodynamic forces instead of the interaction forces in contact manipulation, and hence eliminates the adhesive forces that decrease the chances of achieving successful releases. Motion of the cluster of microparticles results in a pressure gradient (within the vicinity of the microbead in a fluid) that derives and steers the microbeads without contact. The microparticles are moved under the influence of controlled magnetic field gradient to push or pull the microbeads towards reference positions. We achieve non-contact manipulation via pushing and pulling at average speeds of 219 μm/s and 258 μm/s for the microbead, respectively (using cluster of 10 microparticles). The non-contact pushing and pulling localize the microbeads within the vicinity of reference positions with average steady-state errors of 177 μm and 100 μm, respectively. Moreover, we experimentally demonstrate non-contact microassembly of 3 microbeads into an *L-shape* at a task completion time of 25 seconds.

I. Introduction

Manipulation at microscale can be used in diverse biomedical (e.g., manipulation and positioning of biological cells in an aqueous environment) and nanotechnology applications [1]-[7]. One of the main challenges that prevent the automation of manipulation at microscale is the difficulty to make successful releases at the desired position due to the adhesive forces [8]. These adhesive forces result in stickiness between the manipulator and the manipulated object, and thus prevent the release of the object in the desired position. Several techniques have been introduced to overcome the effect of the dominant adhesive forces. Saito *et al.* have proposed the utilization of voltage between the end-effector and the substrate to produce an electric field that assist the sample release [9]. Kim *et al.* have reduced the adhesion between biological cells and microgripper tips by dip coating the tips with 10% SurfaSil siliconizing fluid and 90% histological-grade xylenes for 10 seconds before use [10].

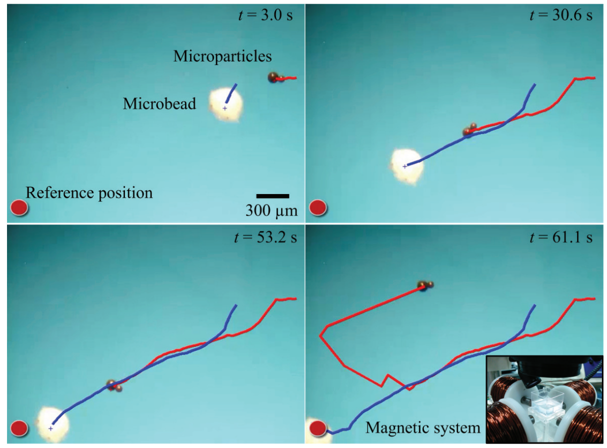

Fig. 1. Non-contact pushing of a microbead (300 μm in diameter) towards a reference position (red circle) using a pair of paramagnetic microparticles. The pair is controlled under the influence of the controlled magnetic field gradients. These gradients are generated using the electromagnetic system shown in the bottom-right corner. Motion of the cluster of microparticles results in a pressure gradient in the fluid. This pressure gradient pushes the bead without any contact with the cluster. After time, $t = 53.2$ seconds, the cluster makes a *u-turn* to localize the bead within the vicinity of the reference position. The non-contact manipulation allows for successful release of the microbead at the reference position (before time. $t = 61.1$ seconds). The blue and red lines indicate the trajectories of the bead and cluster, respectively. *Please refer to the accompanying video that demonstrates the non-contact pushing of a microbead.*

Magnetic microrobotic systems have been also used in micromanipulation to push and pull the microobject towards the desired positions [1], [11]. Manipulation using microrobots can be classified into two categories, i.e., contact [12] and non-contact manipulation [13]. In contact manipulation, the presence of adhesive forces prevents the release of the microobjects, whereas in non-contact manipulation the absence of adhesion facilitates microobjects release. Two dimensional contact and non-contact micromanipulation of microspheres using a mobile microrobot has been achieved by Floyd *et al.* [13]. In the contact mode, the microrobot has been used to push the microspheres, whereas in the non-contact mode the fluid flow caused by the translation of the microrobot generates enough force to push the microspheres. However, this non-contact manipulation has not been implemented using multiple microrobotic agents to control the non-contact driving forces on the microobjects and to allow for coarse and fine non-contact positioning.

This work investigates experimentally the non-contact manipulation of microbeads using clusters of paramagnetic mi-

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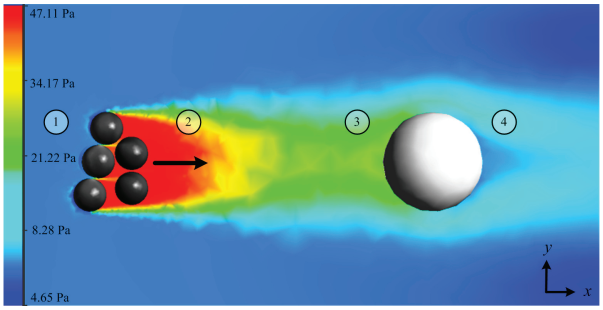

Fig. 2. A finite element (FE) simulation of the pressure gradient in the fluid caused by the motion of a cluster of 5 microparticles. This pressure gradient generates enough force that pushes or pulls the microbead without contact. Motion of the cluster of microparticles is done by the controlled magnetic field gradient. This gradient is generated using an electromagnetic system (not shown). The pressure at points ①, ② and ③ are higher than the that at point ④. The FE model is created using ANSYS (ANSYS 15.0, Inc., Canonsburg, Pennsylvania, USA).

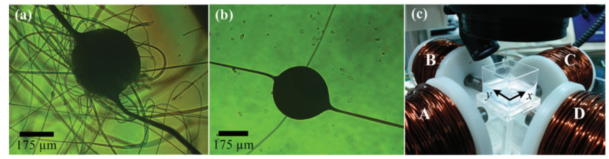

Fig. 3. Steps of fabrication of microbeads with average diameter of 300 μm using electrospinning [14]. The flow rate, voltage, and concentration of the polystyrene in the electrospinning are 3 ml/h, 10 kV and 15%, respectively. (a) Beaded fibers are produced using electrospinning. (b) The beaded fibers are separated using tweezers. (c) The beads and cluster of microparticles (not shown) are contained inside the water reservoir. This reservoir is surrounded by an orthogonal array of electromagnetic coils. The letters A, B, C, and D indicate the electromagnetic coils.

croparticles, as shown in Fig. 1. The utilization of microparticles allows us to change the pressure gradient generated by their motion, and hence achieve different driving non-contact forces on the microbeads. This relation is investigated by measuring the average speeds of the microbeads for different number of microparticles within the clusters. In addition, we implement this non-contact technique to pull and push microbeads towards the reference positions. Furthermore, the non-contact pushing and pulling is used to achieve microassembly of microbeads.

The remainder of this paper is organized as follows: In Section II, we model the non-contact forces between the cluster and microbead due to the pressure gradient caused by the motion of the cluster. We also include descriptions of the fabrication of the non-magnetic microbeads using electrospinning, and characterization of the non-contact pulling and pushing of the microbeads. Section III provides experimental demonstration of the non-contact micromanipulation and microassembly via pushing and pulling. Finally, Section V concludes and provides directions for future work.

II. Modeling and Characterization of the Non-Contact Forces on Microbeads

Microbeads of non-magnetic material are fabricated to study the influence of the non-contact forces generated using a cluster of paramagnetic particles on their motion.

A. Modeling of the Non-Contact Forces

Motion of the cluster of microparticles in a fluid creates a flow within its vicinity. This flow changes the pressure gradient around the cluster based on its size, velocity, and the properties of the fluid. The pressure gradient around the cluster (Fig. 2) generates a non-contact force that could overcome the drag force on the microbead. Respectively, the non-contact force ($\mathbf{F}_{\mathrm{nc}}(\mathbf{P}_{\mathrm{b}})$) is given by

$$\mathbf{F}_{\mathrm{nc}}(\mathbf{P}_{\mathrm{b}}) = m\left(\frac{P_h - P_l}{\rho d}\right)\widehat{\mathbf{n}}, \tag{1}$$

where P_h and P_l are the high and low pressures on the microbead due to the motion of the cluster, and $\widehat{\mathbf{n}}$ and m are a unit vector of the velocity of the microbead and the mass of the fluid, respectively. Further, ρ and d are the fluid density and the distance between the cluster and the microbead. The cluster of microparticles is also subjected to a magnetic force ($\mathbf{F}(\mathbf{P}_{\mathrm{c}})$) that is given by

$$\mathbf{F}(\mathbf{P}_{\mathrm{c}}) = \nabla(\mathbf{m}(\mathbf{P}_{\mathrm{c}}) \cdot \mathbf{B}(\mathbf{P}_{\mathrm{c}})), \tag{2}$$

where $\mathbf{P}_{\mathrm{c}}$ is the position of the cluster of microparticles. Further, $\mathbf{m}(\mathbf{P}_{\mathrm{c}}) \in \mathbb{R}^{3\times 1}$ and $\mathbf{B}(\mathbf{P}_{\mathrm{c}}) \in \mathbb{R}^{3\times 1}$ are the induced magnetic dipole moment of the cluster and the magnetic field at point, respectively. We change the non-contact force by incorporating different number of microparticles in the cluster. Therefore, the we calculate the Reynolds number to investigate the inertial effect in the fluid flow. The Reynolds number (R_{e}) is given by

$$R_{\mathrm{e}} = \frac{2\rho_{\mathrm{f}} v r_{\mathrm{c}}}{\eta}, \tag{3}$$

where v and η are the velocity of the cluster of microparticles and fluid dynamic viscosity (1 mPa.s), respectively. Further, r_{c} is the radius of the cluster. For a cluster of less then 4 microparticles, Reynolds number is calculated to be 0.024 (at average speed of 120 μm/s). For a cluster of 8 microparticles, Reynolds number is calculated to be 0.19 (at average speed of 494 μm/s). The Reynolds number at these two representative number of microparticles indicates that the inertial effect in the fluid could influence the non-contact manipulation of the non-magnetic microbead based on the number of microparticles in the cluster. This inertial effect is used to achieve successful releases by pushing the microbead towards the reference position at low speeds, then making a *u-turn* and moving at higher speed to break free from the microbead and achieve a successful release (Fig. 1).

Motion of microbeads is governed by the pressure gradient in (1) that is created by the motion of the cluster based on (2). When the cluster moves towards the microbead (Fig. 2), the pressure at point ② is greater than that at point ①, and the pressure at point ③ is greater than that at point ④. We model this pressure gradient between a cluster of 5 microparticles and a microbead using ANSYS (ANSYS 15.0, Inc., Canonsburg, Pennsylvania, USA), as shown in

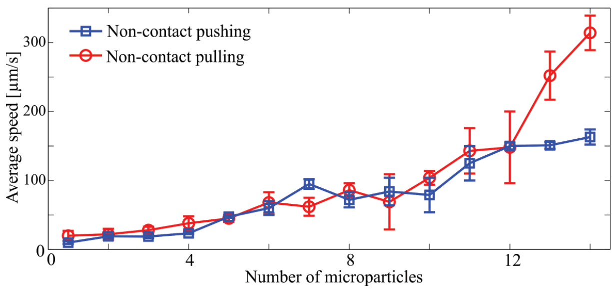

Fig. 4. Average speed of the microbeads versus the number of microparticles within the clusters. The electromagnet coil B is used to pull the cluster by the field gradients during pushing, whereas electromagnetic coil D is used during pulling. These gradients are generated by applying 1.4 A to the electromagnetic coils. The paramagnetic microparticles have an average diameter of 100 μm (PLAParticles-M-redF-plain from Micromod Partikeltechnologie GmbH, Rostock-Warnemuende, Germany).

Fig. 2. In this simulation, the cluster has initial velocity of 20 μm/s, and the pressure at points ①, ②, ③, and ④ are calculated to be approximately 5 Pa, 38 Pa, 20 Pa, and 8 Pa, respectively. Therefore, the microbead is subjected to a non-contact force that could overcome its drag. In order to study the non-contact forces that are exerted on the microbeads, we fabricate them from polystyrene using electrospinning.

B. Fabrication of the Microbeads

Microbeads are fabricated by electrospinning [14] using a solution, i.e., polystyrene and dimethylformamide (Sigma-Aldrich, Taufkirchen, Germany) that is slowly injected through a needle via a syringe pump (CMA 402 Syringe Pump, CMA Microdialysis, Kista, Sweden). An electrical potential is applied to the needle to introduce free charge at the liquid surface. The free charge generates electric stress that causes the liquid to accelerate away from the needle. When the electrical potential rises to a few kilovolts, the liquid meniscus at the needle opening develops into a conical shape. A liquid jet with high charge density is observed at the cone apex where the free charge is highly concentrated. Microbeads or beaded fibers (Fig. 3) are formed for solutions with low viscosity since surface tension is the dominant factor. We decrease the viscosity of the solution and obtain beaded fibers (Fig. 3(a)). The beaded fibers are separated using tweezers and the beads are cut. Parameters of this electrospinning process are provided in Table I. Using these parameters we obtain microbeads with average diameter of 300 μm, as shown in Fig. 3(c).

C. Non-Contact Pushing and Pulling Characterization

Our non-contact micromanipulation via pushing and pulling is based on moving the cluster of microparticles such that the microbead is pushed or pulled towards a reference position. We observe that the size and shape of the cluster of microparticles affect the non-contact pushing and pulling forces that are exerted on the microbeads. Fig. 4 shows the relation between the number of microparticles within the cluster and the average speed of the microbead. The microbeads are pushed or pulled at higher average speeds when

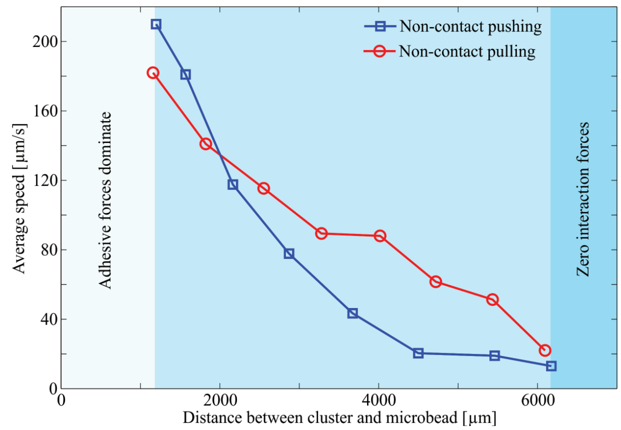

Fig. 5. Average speed of the microbead versus the distance between the centers of the cluster of microparticles and the microbead. A cluster of 10 microparticles is used during pushing and pulling. Speed of the microbead is inversely proportional to the distance between the cluster and the microbead for the pushing and pulling. The paramagnetic microparticles have an average diameter of 100 μm.

the number of microparticles within the cluster increases. This characterization experiment is done using an electromagnetic system with 4 electromagnetic coils (Fig. 3(c)). The effect of the number of microparticles within the cluster on the velocity of the microbead during pushing and pulling is analyzed. This analysis is done by pulling the cluster using the field gradients and measuring the linear velocity of the microbead for different number of microparticles. The number of microparticles per cluster is varied from 2 to 16 microparticles. The average speed is calculated from 5 pushing and pulling trials. One electromagnet is used in pushing and pulling to drive the cluster along x-axis. In these experiment, microbeads with similar size are used and the non-contact pulling and pushing are done between similar initial and final positions within the workspace of

TABLE I

PARAMETERS OF THE ELECTROSPINNING PROCESS AND THE ELECTROMAGNETIC SYSTEM: POLYSTYRENE IN A SOLUTION OF DEMETHYLFLOURINE IS USED TO FABRICATE MICROBEADS WITH AVERAGE DIAMETER OF 300 μM. THE ELECTROMAGNETIC SYSTEM CONSISTS OF ORTHOGONAL ARRAY OF 4 ELECTROMAGNETIC COILS. THE MAGNETIC FIELDS ARE MEASURED AT THE CENTER OF THE WORKSPACE USING A CALIBRATED 3-AXIS DIGITAL TESLAMETER (SENIS AG, 3MH3A-0.1%-200MT, NEUHOFSTRASSE, SWITZERLAND).

Parameter	**Value**	**Parameter**	**Value**
Voltage [kV]	10	Flow rate [ml/h]	3
Concentration [%]	15	Electrode spacing [cm]	14
max I_i [A]	1.4	Number of turns	1600
$\|\mathbf{B}(\mathbf{P})\|$ [mT]	16	$\nabla\|\mathbf{B}(\mathbf{P})\|$ [T.m^{-1}]	1.62
$B_x(\mathbf{P})$ [mT]	11.5	$\frac{\partial B(\mathbf{P})}{\partial x}$ [T.m^{-1}]	0.49
$B_y(\mathbf{P})$ [mT]	11.5	$\frac{\partial B(\mathbf{P})}{\partial y}$ [T.m^{-1}]	0.37
r_p [μm]	50	Workspace [mm^3]	1000
η [mPa.s]	1.0	Frame per second	10

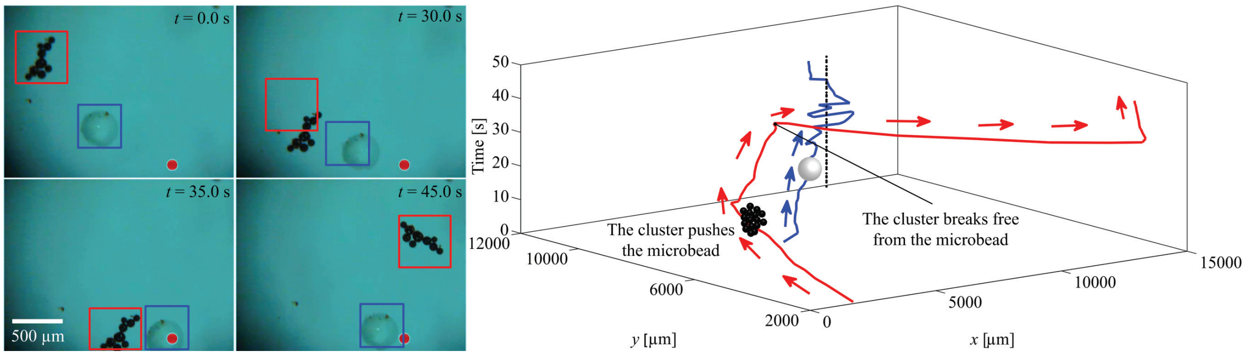

Fig. 6. A representative teleoperation experiment of non-contact pushing of a microbead towards a reference position using a cluster of microparticles at different time instants (t). The cluster pushes the microbead under the influence of the controlled magnetic fields. In this micromanipulation experiment, the velocity of the cluster is 494 μm/s and 2129 μm/s before and after the positioning of the microbead, respectively. The average velocity of the bead is 219 μm/s. The red and blue rectangles represent the position of the cluster and the microbead, respectively. The cross hair indicates the reference position. The graph (right) plots the trajectory of both the cluster and the microbead throughout the experiment. Paramagnetic microparticles with average diameter of 100 μm are used in this experiment. *Please refer to the attached video that demonstrates the results of the magnetic-based non- contact micromanipulation of the microbead by pushing using a cluster of microparticles*

our magnetic system for all trails. In addition, the distance between the cluster of microparticles and the center of the microbead is kept constant during the calculation of the data provided in Fig. 4.

The effect of the distance between the cluster of microparticles and the microbeads is also studied. We measure the distance between the cluster and the microbead (during pushing and pulling) and the corresponding average speed of the microbead for each distance. Fig. 5 shows a representative relation between the distance between the cluster and microbead and the average speed of the microbead during pushing and pulling. A cluster of 10 microparticles is used to push and pull a microbead with diameter of 300 μm within the center of the workspace of our magnetic system. This experiment is done under the influence of a uniform magnetic field. We observe that when the distance between the cluster and the microbead is approximately 1200 μm the adhesive forces dominate and non-contact pushing or pulling cannot be achieved. The pushing and pulling speeds decreases as the distance between the cluster and the microbead increases. The pressure gradient of the cluster becomes negligible when the distance is greater than 6000 μm.

III. Experimental Non-Contact Micromanipulation and Microassembly

Our experimental motion control results include non-contact pushing and pulling of microbeads towards reference positions, and non-contact microassembly of multiple microbeads. Positions of the cluster, microbead and the reference position are determined by a teleoperation control system to move the cluster behind or in front of the microbead to achieve non-contact pushing and pulling, respectively. The clusters of microparticles and the microbeads are contained in water reservoir that is surrounded with 4 electromagnetic coils. The magnetic properties of the electromagnetic configuration is provided in Table I. The magnetic fields are measured using a calibrated 3-axis digital Teslameter (Senis AG, 3MH3A-0.1%-200mT, Neuhofstrasse, Switzerland). The microparticles that are used in these experiments are paramagnetic (PLAParticles-M-redF-plain from Micromod Partikeltechnologie GmbH, Rostock-Warnemuende, Germany) with an average diameter of 100 μm.

A. Manipulation of Microbead via Non-Contact Pushing

Non-contact micromanipulation of microbeads within the vicinity of the reference positions is done, as shown in the representative experiment in Fig 6. In this experiment, a cluster of 9 microparticles is used to drive a microbead with diameter of 300 μm. The average speed of the cluster is calculated to be 494 μm/s and 2129 μm/s before and after the positioning of the microbead at the reference position, respectively. The average speed of the microbead is calculated to be 219 μm/s. The time taken to drive the microbead from the initial position to the reference position (vertical black line) is 35 seconds. This experiment shows that the cluster achieves successful positioning and release of the microbead within the vicinity if the reference position with an error of 259 μm along x-axis and 66 μm along y-axis. *Please refer to the accompanying video that demonstrates a representative non-contact pushing of a microbead towards a reference position.*

We repeat the non-contact micromanipulation using pushing 3 times and the average positioning time is calculated to be 30 seconds, whereas the average position errors are 190 μm along x-axis and 70 μm along y-axis. We observe that using non-contact pushing it is easy to release the microbead precisely at the reference position. However, this accuracy is affected when the cluster moves away from vicinity of the reference position and microbead (as shown in Fig. 6 at times, $t = 35$ seconds and $t = 45$ seconds).

B. Manipulation of Microbead via Non-Contact Pulling

Non-contact pulling of microbeads is achieved, as shown in Fig. 7. A cluster of 5 microparticles are controlled under the influence of the magnetic field gradient and positioned

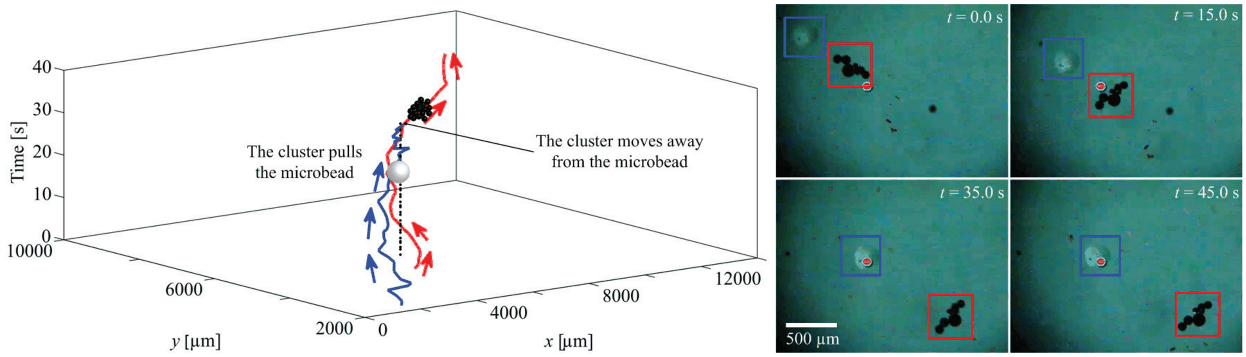

Fig. 7. A representative teleoperation experiment of non-contact pulling of a microbead towards a reference position using a cluster of microparticles at different time instants (t). The cluster pulls the microbead under the influence of the controlled magnetic fields. In this micromanipulation experiment, the average velocity of the cluster is 298 μm/s and 854 μm/s before and after the positioning of the microbead at the reference position, respectively. The average speed of the microbead is 258 μm/s. The red and blue rectangles represent the position of the cluster and the microbead, respectively. The cross hair indicates the reference position. The graph (right) plots the trajectory of both the cluster and the microbead through out the experiment. Paramagnetic microparticles with average diameter of 100 μm are used in this experiment. *Please refer to the attached video that demonstrates the results of the magnetic-based non- contact micromanipulation of the microbead using a cluster of microparticles*

between the reference position and the microbead. Motion of the cluster generates a pressure gradient in the fluid and achieve pulling of the microbead towards the reference position. The average speed of the cluster and microbead are calculated to be 75 μm/s and 30 μm/s, respectively. The time taken to pull the microbead from its initial position to the reference position is 30 seconds. The cluster localizes the microbead within the vicinity of the reference position and also achieves successful release with an error of 300 μm along x-axis and 200 μm along y-axis. *Please refer to the accompanying video that demonstrates a representative non-contact pulling of a microbead towards a reference position.*

The non-contact micromanipulation using pulling is repeated 3 times and the average positioning time is calculated to be 25 seconds. The average positioning time of micromanipulation using pulling is less than that using pushing since the average speed of pulling is greater than the average speed of pushing (Figs. 4 and 5). We also observe that the non-contact micromanipulation via pulling achieves successful releases easily as in the non-contact pushing. The average position errors are calculated to be 110 μm along x-axis and 45 μm along y-axis.

The speed of the cluster of microparticles during non-contact pushing and pulling affects the release of the microbead and also affect the positioning accuracy. During the micromanipulation, our control system maintains a steady speed of the cluster of microparticles. Once the microbead reaches the reference position, the speed of the cluster increases to break free form the non-contact forces between the cluster and the microbead. In the representative non-contact micromanipulation via pushing (6), the speed of the cluster before and after the positioning of the microbead are 494 μm/s and 2129 μm/s, respectively. In the non-contact micromanipulation via pulling the (Fig. 7), the speed of the cluster before and after the positioning of the microbead at the reference position are calculated to be 298 μm/s and 894 μm/s, respectively.

C. Microassembly of Multiple Microbeads

Non-contact microassembly is achieved using pushing and pulling. We demonstrate that a cluster of microparticles can assemble single row of 3 microbeads. This experiment is done using a cluster of 40 microparticles. The initial positions of the microbead is shown in Fig. 8 (at time, $t = 0$ seconds). The cluster is moved under the influence of the controlled magnetic fields towards microbead ①. The cluster achieves non-contact pushing of this microbead towards microbead ② at time, $t = 25$ seconds. The adhesive forces forms a single row of microbeads ① and ② while the cluster moves away from their vicinity. After time, $t = 60$ seconds, the cluster moves behind microbead ③ and starts a non-contact pushing towards the 2 assembled microbeads (① and ②). At time, $t = 360$ seconds, the cluster moves away from the vicinity of the 3 assembled microbeads. Although the assembly time of the microbeads into single row is approximately 360 seconds, we observe that successful releases are achieved at each time. The orientation of the assembled microbeads can be adjusted by the cluster also without contact. *Please refer to the accompanying video that demonstrate the non-contact microassembly of 3 microbeads.*

IV. CONCLUSIONS AND FUTURE WORK

We demonstrate experimentally that a cluster of paramagnetic microparticles can be used to achieve non-contact micromanipulation of microbeads of non-magnetic material (polystyrene). The motion of the cluster is controlled under the influence of the magnetic field gradient to change the pressure gradient within the vicinity of the microbead. This pressure gradient allows us to exert non-contact forces on the microbeads, and hence achieve accurate positioning and successful releases at the reference positions. We demonstrate non-contact positioning via pushing and pulling with average steady-state errors of 177 μm and 100 μm, respectively. The non-contact micromanipulation achieves successful releases by moving the microbeads towards the reference positions

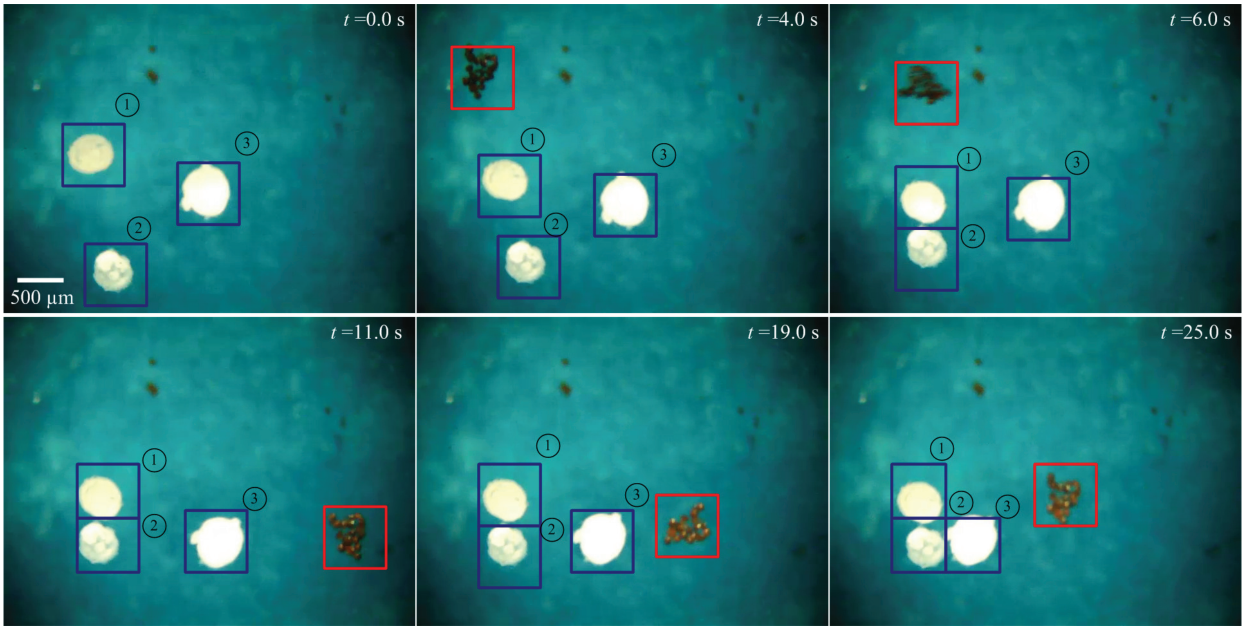

Fig. 8. A representative teleoperation experiment of non-contact microassembly of 3 microbeads using a cluster of microparticles at different time instants (t). The cluster pushes and pulls the microbeads without contact under the influence of the controlled magnetic fields to form an *L-shape* of 3 microbeads connected together (at time, t=25 seconds). In this microassembly experiment, the average speed of the cluster is 300 μm/s. The cluster consists of 15 microparticles. Paramagnetic microparticles with average diameter of 100 μm are used in this experiment. *Please refer to the attached video that demonstrates the results of the magnetic-based non-contact microassembly of multiple microbeads using a cluster of microparticles.*

at a steady-speed of the cluster. Once the microbead reaches the reference position, the cluster breaks free from the non-contact forces by moving with speeds that are 4 and 3 times higher than the steady-speed of the non-contact pushing and pulling, respectively. In addition, we experimentally demonstrate non-contact microassembly of several non-magnetic microbeads into an *L-shape* in a task completion time of 25 seconds with successful release.

As part of future studies, non-contact micromanipulation of microobjects will be done in three-dimensional (3D) space. This control would allow us to use non-contact micromanipulation in diverse nano-technologies that necessitates assembly of complex shapes in 3D space. In addition, our electromagnetic system will be adapted to incorporate force sensors that would allow us to measure the non-contact pushing and pulling forces that are exerted on the microbeads.

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