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Micro Manipulation based on Adhesion Control with Compound Vibration

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Abstract—**Due to scale effects, the releasing of micro objects has been a long-standing challenge in micromanipulation applications. In this paper a micromanipulation system is presented based on the adhesion control with compound vibration. This adhesion control technique employs inertia force to overcome adhesion force achieving 100% repeatability with releasing accuracy of 4± 0.5μm, which was experimentally quantified through the manipulation of 20-100μm polystyrene spheres under an optical microscope. The micromanipulation system consists of a microgripper and a piezoelectric ceramics module. The compound vibration comes from the electrostatic actuator and the piezoelectrically driven actuator. Surface and bulk micromachining technology is employed to fabricate the microgripper used in the system from a single crystal silicon wafer. Experimental results confirmed that this adhesion control technique is independent of substrate. Theoretical analyses were conducted to understand the releasing mechanism. Based on this preliminary study, the micromanipulation system proves to be an effective solution for active releasing of micromanipulation.**

Index terms-**Microelectromechanical systems (MEMS), microgripper, micromanipulation, adhesion control, compound vibration**

I. Introduction

Micromanipulation and microassembly are important emerging techniques that serve as enabling techniques for a wide variety of applications in biological and biomedical research, as well as in the assembly of microelectromechanical systems (MEMS) and microelectronic devices [1]-[4]. With the development of miniaturization, decreasing the scale brings us to technological limits such that it seems to be necessary to use intrinsic properties of the considered scale. Among the challenges, a long-standing difficulty in the manipulation is the release of micro objects from the end-effector due to the adhesion forces at the microscale. Scale effects cause adhesion forces including the van der Waals force, electrostatic force, and capillary force to dominate volumetric forces (e.g., gravity) [5].

Currently, there are two types of release methods in the micromanipulation systems, passive release and active release. Passive release techniques mainly depend on the strong adhesion substrate. In consideration of adhesion and rolling resistance factors [6], an Au-coated substrate is used for both picking and releasing operation. Microspheres were rolled on the special substrate causing the fracture of the sphere-substrate interface and the sphere-tool interface, respectively. Similarly, it was also demonstrated that fixing miniscule glass spheres on a sample table by an ultraviolet cure adhesive [7]. A commonality of passive releasing technique is the dependence on surface properties, time consuming, and poor in repeatability.

Differently, active release methods intend to detach the micro object from the end-effector without touching the substrate. A commonly method of active releasing is using vacuum tools [8], [9] to create a pressure difference for picking and release. However, miniaturization and accurate control of vacuum tools can be difficult, and sometimes its use in a vacuum environment can be limited. In [10], [11], Freeze tweezers were used to pick micro objects, and thawing of the ice was used to release micro objects. The approach requires a complex end effector and is limited to micromanipulation in an aqueous environment.

Micromanipulation systems with MEMS microgrippers [12], [13] have also been widely reported. As the key technology, these double-ended microgrippers could pick the micro objects easily and provide a sufficient clamping force. However, it is difficult to achieve effective releasing of micro objects since the adhesion force between the objects and one of the gripping arms. Some methods are used to reduce the adhesion force. For example, surface roughening of gripping arms [14], chemically coating gripping arms [15] and changing the surface characteristics [16]. Nevertheless, the effectiveness of gripping arm treatment for releasing is limited since of the residual adhesion forces is still strong enough to keep the micro object adhered to a gripping arm. An active releasing strategy by using a MEMS microgripper that integrates a plunging structure between two gripping arms is present in [17]. 7.5–10.9μm microspheres were picked and released easily.

Considering the operation strategy, a type of active releasing makes use of mechanical vibration [18], [19]. The vibration method takes advantage of inertial effects of both the end-effector and the micro object to overcome adhesion

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forces. The landing radius of the released object has been calculated and simulated in [20], however, the accuracy of this single vibration has not been experimentally quantified.

In this paper, we present a micro manipulation system based on active releasing strategy by adhesion control with compound vibration. The operation tools consist of a MEMS microgripper and a piezoelectric ceramics, as shown in Fig. 1. The microgripper is actuated by electrostatic actuator and fixed on the PZT. This strategy retains the advantage of double-ended tools for picking up micro objects. The compound vibration caused by the PZT and the microgripper arms is capable of placing a micro object adhered to a gripping arm to a desired destination on a substrate, enabling highly repeatable releasing with a high accuracy. In addition, in order to improve the gripping performance, the microgripper arms integrate sidewall piezoresistive force sensors to sensing the gripping force. Protective beams are design to prevent gripper arms broken during the operation. Finally, successful manipulation of 20-100μm microspheres under optical microscope for capturing and releasing are presented using this strategy.

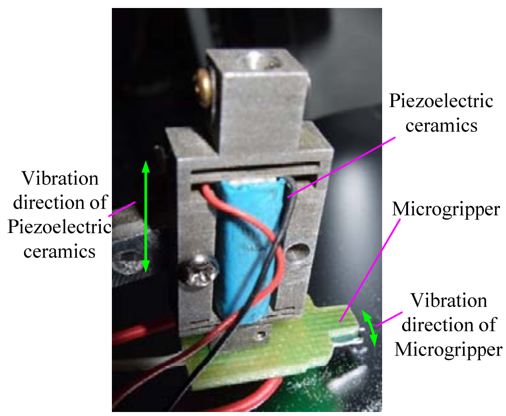


Fig. 1 The composite operational tool.

I. Design of the Micromanipulation System

A. Configuration

The experimental setup consists of macro moving precise positioning stages, piezoelectric actuator, microgripper, and micro-vision systems. The system can operate objects of a size ranging from 20μm to 100μm.

The composite operational tool is the key to entire operating system. In order to make better use of inertial effects, an additional compound vibration is introduced with a vertical vibration and a horizontal vibration in plane. The theoretical analysis of the compound vibration will be presented in the third section. The vertical vibration is achieved by the PZT, and the two microgripper arms vibrate relatively in the operation plane actuated by sinusoidal AC signal. The objects in the middle of two arms could be positioned effectively under the action of compound vibration.

B. Design of the Microgripper

Fig. 2 shows a schematic model of the microgripper. This typical microgripper consists of flexible beams, electrostatic comb fingers, force sensor beams (as the gripper arms), glass substrate, and bonding pads. The end-effectors of the gripper is processed in a single standard silicon wafer (i.e., no silicon on insulator wafer is used), which realizes the miniaturized grippers with end-effectors on the size-scale of the manipulated objects. The electrostatic actuator generates a linear horizontal motion, which is converted into rotation of the arms by an S-type flexible beam system. The movable structure is supported by the flexible composite suspending beams. The substrate material is glass which can serve as an insulation function to the gripper. The integral dimension of the microgripper is 6.2 × 3.0 × 0.8mm. This gripper can operate objects of sizes ranging from 0 to 100μm.

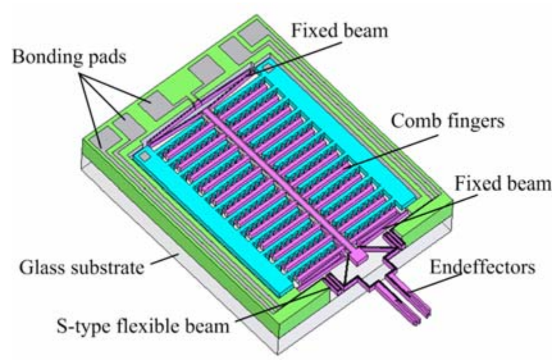


Fig. 2. Model of the microgripper.

Surface and bulk micromachining technology is used to fabricate microgrippers from silicon wafers. The fabrication sequence is illustrated in Fig. 3.

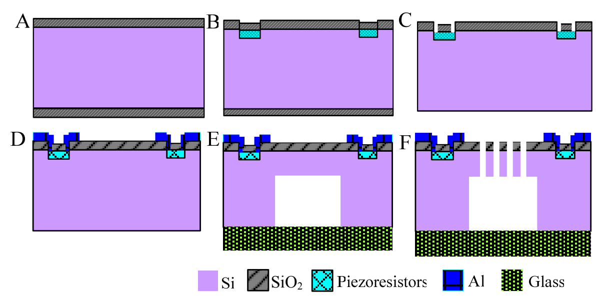


Fig. 3 Process sequence of microgripper fabrication.

The starting material was 4-inch, N-type, (100) orientation, 1-10Ωcm double polished silicon wafer with a thickness of 300μm. The SiO_2 layer thickness was controlled to be approximately 0.5μm, and then buffer HF acid etching SiO_2 with photoresist as the etching mask. The piezoresistors were formed by boron diffusion process. The contact holes are patterned by photolithography and opened by wet etching in buffered HF solution. 1 μm-thick aluminum wires and bonding pads were formed by vacuum evaporation, photolithography, and etching processes. The releasing windows in the backside of wafer were patterned by photolithography. Then DRIE Bosch process was used to thin the device regions to 50μm with photoresist (AZ9260) as the etching mask. Then the glass wafer and silicon wafer were bonded together to form the support base. And the glass becomes the nonconductor for the electrostatically driven. With patterned photoresist and SiO_2 layer as the etching mask, the mechanical structure and the vertical sidewall surface are formed by using DRIE. In order to ensure the identical dimension of each piezoresistor, the parameters of the DRIE should be controlled strictly.

Force sensor in the dynamic system occupied a secondary part, the detailed fabrication and using of the sensor can be found in [21]. It would not be introduced in this paper.

C. The piezoelectric actuator

The piezoelectric ceramic element is a component that transfers energy between electrical and mechanical states. Therefore, it can be used in different applications, e.g. the sensor, the actuator, etc. In this paper, the PZT driver is used to generate vibration acceleration. In this paper, the PZT driver used is as same as in [21]. Differently, it is used to generate vibration acceleration in the system not the gripper action.

II. Adhesion control of compound vibration

The adhesion phenomena are mainly a result of intermolecular potentials, as expressed by Van der Waals forces. Capillarity and electrostatic are also environment dependent forces that contribute to the adhesion. For micro-scale objects, these forces have higher magnitudes than the gravitational force and they are mainly attractive. Nevertheless, they depend on the inverse square or cube of the distance between the surfaces, for example, for Van der Waals, and their influence becomes obvious in contact. A minimum amount of force is thus necessary to separate two mediums in contact. This force is commonly called pull-off. In the case of a sphere (radius R_b) on a planar surface, its expression is approximately given by the JKR (for the lower boundary) contact models [20]

$$F_{ext} > \frac{3}{2}\pi R_b \gamma_{bb} \tag{1}$$

where γ_{bb} is the adhesive energy between microparticle and microparticle.

Specifically micro-manipulations are the main subject of this work. That is, manipulating objects of submillimeter in size, and working with distances of the order of micrometers. The aim is to establish a general micromanipulation system using characteristic forces at the microscale. To understand the system, a classical example of micro-spheres manipulation has been chosen. Dynamical modelling is thus achieved using this example where the main particularity is to illustrate the main characteristics of the problem. The aim is to pick up and release a stack of 10-50μm radius balls located on a substrate and to align them on the same substrate. To perform this manipulation by adhesion control the microgripper is used. Indeed, dynamical modelling must allow us to study material combinations, acceleration of the gripper for the capturing and the releasing.

The manipulation task concludes in picking up a sphere initially laying on a silicon wafer surface using gripper, and then placing it on a selected location on the same substrate. Considering this simple task, the process can be decomposed into 4 basic phases. First, the end-effector is brought in contact with the object. The capture is accomplished by taking advantage of stronger gripping forces of the microgripper. In order to avoid adhesion of other balls, the vibration of microgripper is employed in the lifting stage as shown in Fig. 4.

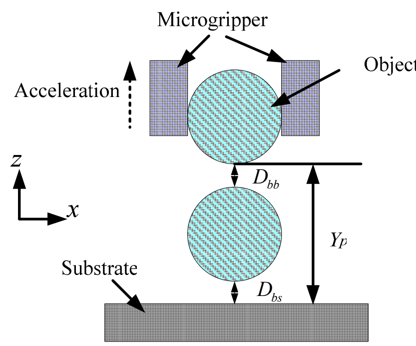


Fig. 4 Model of dynamic pickup.

The object is then brought in contact with the substrate at the release location. To achieve the releasing, the adhesion between the end effector and the object must be overbalanced. This can be accomplished by the compound vibration of the end-effector and the whole gripper to reduce the adhesion force, which would be mentioned later. Firstly, by writing dynamic equilibriums of the all components of the system, a simplified dynamic model of pickup can be obtained [22]:

$$m_p \ddot{Y}_p = F_{ext} - F_{bb}^{ad} - m_p g \tag{2}$$

$$m_b \ddot{D}_{bs} = F_{bb}^{ad} - F_{bs}^{ad} - m_b g \tag{3}$$

$$Y_p = D_{bs} + D_{bb} + 2R_b \tag{4}$$

m_p, m_b are respectively the masses of the gripper arms and the micro-object, F_{ext} is the external force applied to the arms and F_{bb}^{ad} and F_{bs}^{ad} are respectively the adhesion forces between the object and the arms and the object and the substrate, including Van der Waals, electrostatic and capillary forces. These forces are non-linear functions of distances $D_{bs,bb}$. R_b is the radius of the object, which is supposed to be a perfect sphere.

In the releasing stage, the microsphere keeps adhering to one gripping arm by adhesion forces. If the microsphere adhered to the left arm, with the vibration of the two arms, the microsphere travels non-directionally as shown in Fig. 5(a). On the other hand, if the vibration of z direction applied solely, the microsphere is applied by the gravitation force and the adhesion-force together. The direction of composite force is lower left corner. Ultimately, the microsphere is released by the single arm, as shown in Fig. 5(b). Both of these two methods can not guarantee accuracy of releasing. In order to achieve accurate releasing, the compound vibration is considered. Those are the vibration induced by piezoelectric ceramic in the z direction and the vibration of two arms in the xy plane. In order to take full advantage of substrate adhesion and get the best releasing results, the microsperes contact with the substrate in the releasing process as shown in Fig. 6. N_s is the normal force from the substrate, f_s is friction force and F_s is the adhesion force. N_p is the laterally pushing force applied by the right gripping arm, and f_p is the adhesion force from the gripping arm.

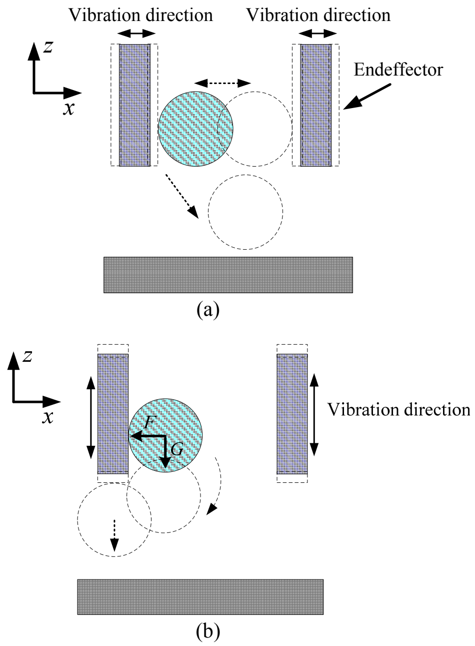


Fig. 5 Model of dynamic release. (a) Arms vibrate only, and (b) PZT vibrates only

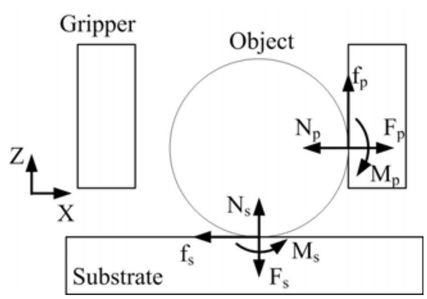


Fig. 6 The principle of release by compound vibarition

On the assumption of a quasistatic process, the equilibrium equations for the object

$$f_p = F_s - N_s \tag{5}$$

$$f_s = F_p - N_p \tag{6}$$

and for the arm

$$F_x = f_s \tag{7}$$

$$F_z = f_p \tag{8}$$

Then, a simplified dynamic model of release along the X (or Z) axis can be obtained similar to the formula (2)-(4). Although increasing the vibration acceleration can achieve the pickup or release operation, but the exorbitant acceleration will increase the degree of non-directional movement of the microobjects and affect the steady pickup and accurate release operation. Therefore the minimum vibration acceleration is the key of the valid operation. The minimum acceleration of pickup and releasing can be obtained by the simulation and computing. The relation curve of the minimum release acceleration and the diameters of polystyrene microsphere can be obtained and shown in Fig. 7. Suppose the microspheres are released on the silicon substrate.

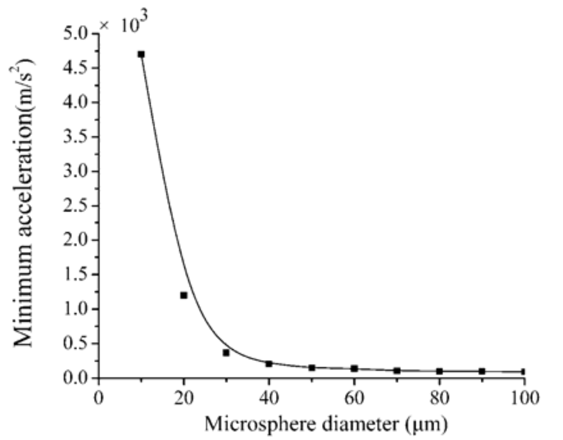
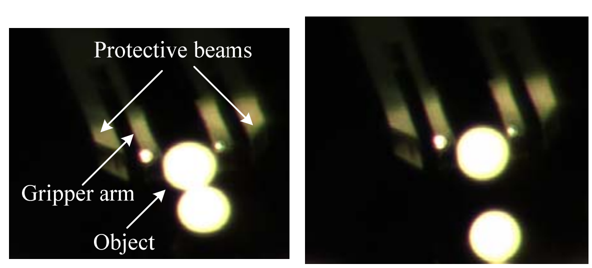


Fig. 7 The minimal acceleration of release vs microsphere diameters.

III. EXPERIMENTAL RESULTS

A test setup was established to characterize the performances of the dynamic manipulation. This typical system consists of macro moving precise positioning stages, piezoelectric actuator, microgripper and micro-vision systems. A composite operational tool consists of the PZT and microgripper was mounted on the positioning stages at a tilting angle of 30°. The test was carried out at room temperature of 20±3°C with relativehumidity of 40 ±5%.

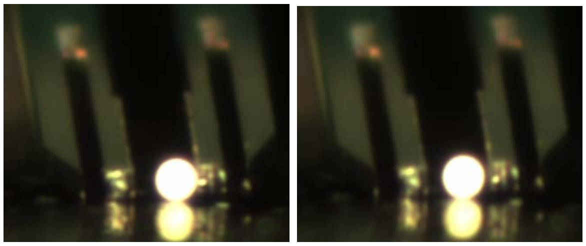
Aimed to the microscale manipulation, the studies of steady pickup, effective releasing and accurate position are experimented with different environments and different sizes of microsamples. Through the summary of the factors in the micromanipulation, the initiative on microoperation to avoid microscale force interference is analyzed and experimented. Fig. 8 is the picture of the dymamic pickup. Left picture shows the adhesion between the microspheres when the object was capture. To get rid of the interference of other microsphere, an instant acceleration of capturing operation is applied shown as the right picture, then the object is captured effeciently.



(a) (b)

Fig. 8 (a) Ball adheres to one arm and b) PZT vibration used

In order to increase the hydrophobicity, a special deal was carried out to the microgripper arms. They were modified with a self-assembled monolayer of FAS-17(fluoro-alkyl silanes). The FAS-17 has good hydrophobicity. In addition, the surface of arms was also dealt with rough treatment. These processes would reduce adhesion significantly in the releasing process. The compound vibration effects is shown in Fig. 9. As the model of rough surface coating is complex, it is not taken into account in the model of operation.



(a) (b)

Fig. 9 (a) Microspere adheres to one arm and (b) compound vibration used.

An experiment of releasing 40μm polystyrene microspheres with different sizes is performed with the system. Firstly, to characterize the releasing performance, single microspheres were repeatedly picked and released from different heights (20–100μm) above the substrate. Fig. 10 shows representative data of landing positions on the silicon substrate. The results show a relationship between landing positions and heights from the substrate, indicating that forces including the van der Waals forces and the electrostatic forces from both the substrate and the microgripper, as well as the gravitational force, do not have a significant effect on the microsphere that travels a short distance in air. The precision of landing is inversely proportional to the height from the substrate, partly due to the more pronounced airflow effect. And corresponding theoretical analysis, In order to take full advantage of substrate adhesion and get the best releasing results, the microspheres contact with the substrate in the releasing process.

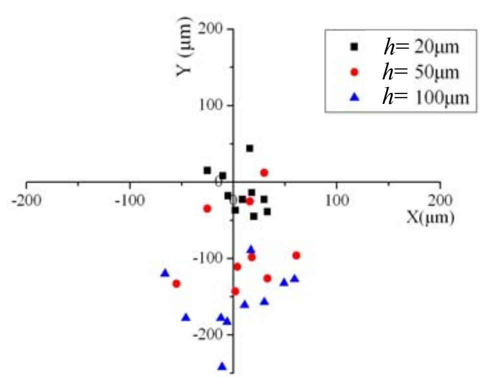


Fig. 10 Landing positions of microspheres. *h* is the height of the gripping arms from above the substrate.

Combined with theoretical calculations and the actual situation, different vibration accelerations are programmed. In which PZT vibration acceleration is supplied from the PZT drive power and vibration acceleration of microgripper arms is supplied from the sinusoidal AC power.

According to peak acceleration formula $a=4\pi^2 f^2 A$, acceleration a and frequency f are proportional to the square. Small change of the frequency will make acceleration value have a greater change. The amplitude A has linear relationship with acceleration and it is easy to be controlled. Therefore, in the experiments, we fix output frequency of the PZT and the gripper, and generate different vibration acceleration by increasing the amplitude of PZT and the gripper arms. In the experiments, two compound vibrations were applied the instantaneous drive at the same time, the duration time is 100ms. TABLE I shows that the minimum acceleration corresponding to the different micro-spheres in pickup operation, in which the reliable amplitude value is the maximum amplitude value of each group result. TABLE II shows that the average minimum acceleration corresponding to the different micro-spheres in release operation.

TABLE I
THE MINIMUM ACCELERATION CORRESPONDING TO THE DIFFERENT MICRO-SPHERES IN PICKUP OPERATION.

Micro-sphere diameter (μm)	30	40	50	60	80
Average amplitude value (μm)	5.6	3.7	3.2	2.7	2.1
Pickup acceleration value (m/s^2)	143	95	82	69	54

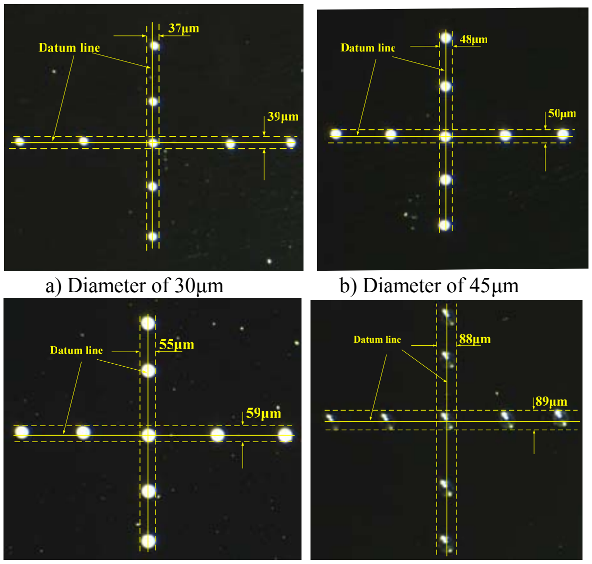
The pickup acceleration value is lower than the theoretical value, and valid pickup can be easily achieved. The success rates of pickup operation come up to 90%. The reason is that the pull-off forces calculated in the simulated analysis is theoretical value. However, the practical impact of environmental and the substrate play a significant role in the experiment. The mciroscale force between the ball and substrate is larger than the theoretical values. Further studies are needed about this point.

TABLE II
THE MINIMUM ACCELERATION CORRESPONDING TO THE DIFFERENT MICRO-SPHERES IN RELEASE OPERATION.

Micro-sphere diameter (μm)	30	40	50	60	80
Average amplitude value (μm)	7.4	4.8	3.7	3.4	2.4
Release acceleration value (m/s^2)	189	123	95	87	61

From TABLE II, we can see that, the minimum acceleration decreases with the increase of microparticle diameter. The minimum acceleration value, obtained from the experiments, lower than the theoretical value. Since the surface of the actual micro-gripper has the hydrophobic layer and the small protrusions, which is designed to increase the roughness. These designs reduce the effect of the micro-scale forces. The results also prove that the compound vibration can effectively reduce the dynamic parameters and achieve stable and accurate release effect.

Fig. 11 shows the result of a series of releasing of microspheres. The releasing point range is calculated at a fixed coordinate system. We can get that an accuracy of 4 ± 0.5μm for the microspheres release. In the figure the spheres of diameters 30, 45, 50, 80μm are arranged respectively. The cross-shaped arrangement is conducive to the calculation of position accuracy. The solid lines are the datum, and dotted line is the boundary region of release. The deviation between the lines can be calculated as the accuracy of release.



a) Diameter of 30μm b) Diameter of 45μm

c) Diameter of 50μm d) Diameter of 80μm

Fig. 11 Stability of microspheres release experiments

IV. CONCLUSION

In this paper a micro manipulation based on an active releasing strategy by adhesion control with compound vibration is presented here. This operation strategy employs inertia force to overcome adhesion force achieving 100% repeatability with releasing accuracy of 4± 0.5μm, which was experimentally quantified through the manipulation of 20-100μm polystyrene spheres. The piezoelectric actuator and the electrostatic driven supply the mutual perpendicular vibrations which generate enough force to overcome the adhesion forces. The manipulation mode combined PZT and the microgripper can ensure the accuracy of releasing operation. This paper revealed that the most important operating parameters are the vibration acceleration and the height from the substrate. With the experiments, the theory and practice experience are provided for the design of micromanipulation system.

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