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Pick and Place of Hard Disk Media using Electrostatic Levitation

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Abstract— **This paper focuses on a practical application of handling contact sensitive objects such as silicon wafers or hard disk media without any contact using electrostatic levitation. Stable electrostatic levitation can be realized by controlling an electrostatic force on the basis of measured suspension air gaps. Two control approaches, namely centralized and de-centralized control and the influence of an integrator in the controller, are discussed with regard to the specific tasks of Pick Up and Place. The final goal is to realize a handling tool that allows human operators to perform these object handling tasks. In this paper a linear motor is used to perform the Pick Up and Place task to allow a controllable and reproducible motion. The experimental results show a stable Pick Up and Place motion, where placing is realized without any external control commands.**

I. INTRODUCTION

In industries processing highly integrated semiconductor devices, glass plates of Flat Panel Displays (FPD), or other contact sensitive material such as hard disk media, these objects are mainly being handled with direct mechanical contact through carrier spatula. The two major problems in handling these sensitive objects are contamination on the product surface by dust particles [1] and structural deformation or damage.

Contamination through contact- and tribo-electrification, which attracts dust particles, can be prevented by contactless object handling. Contactless handling means that the object will be levitated at a certain air gap by a levitation force, similar to non-contact bearings, such that there is no physical contact between object and levitation tool. If the levitation force that suspends the object is distributed over the total area of the object, internal deformation can be significantly reduced. This is especially important for objects where the area/thickness ratio is very large (e.g. FPD glass plates) as bending of these objects causes large stresses in the material.

Some non-contact manipulation- and transportation apparatus have been developed to overcome these problems. They include devices based on magnetic [2], air [3], and acoustic [4] levitation. However, a magnetic force cannot directly levitate nonferromagnetic material and is only used to support the carrier spatula. Air and acoustic levitation have the drawback that they are not suitable for vacuum environments.

Most promising results have been realized based on electrostatic levitation. This technique, which has been employed in a vacuum gyro [5] and microbearings [6], can also be used to levitate silicon wafers [7], hard disk media [8] and even dielectric materials such as glass [9]. However, there is no previous study that has really discussed using an electrostatic levitator for pick and place behavior in which the levitator is moved to the object. These tasks are essential in the realization of a practical tool for contactless object handling.

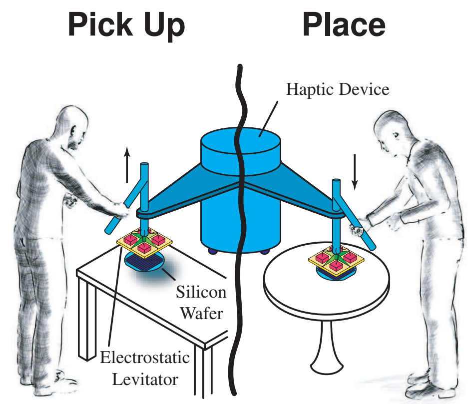

Fig. 1. Concept of handling tool for Pick and Place of wafer without contact. The operator is assisted by a haptic device and moves a silicion wafer from one location to another.

In this paper, pick and place behavior in electrostatic levitation is studied to find a new handling tool that allows human operators to handle those sensitive objects without contact. The handling processes that are typically used for transportation and handling these objects are mainly automated using robots. Still, human handling is often required in for instance the developing process, quality control or very specialized production processes. The human performance in accuracy, tremor free motion, and endurance is limited compared to robots, but they are more flexible and intelligent.

The handling tool discussed here is based on the "Haptic Tweezer" concept [10] in which non-contact levitation techniques are combined with a haptic device and it was verified based on magnetic levitation. In this concept, the performance of contactless handling is increased by giving realtime force feedback to the operator, depending on the stability of the levitation system. This can be necessary as a levitated object is more sensitive to external disturbances (e.g. sudden motion or tremors). The haptic device assists in performing an object handling task such as pick and place by restricting the operators motion if this motion could cause instability. A haptic force directly related to the levitation position error prevents motion disturbances from the operator. Free motion is allowed when the levitation

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position error of the object is approximately zero. It was verified that especially in the Pick Up and Place task, where large position errors are imposed, improvement of contactless handling could be realized.

In the Place task special attention has to be given to releasing the object in a intuitive way. An automatic release, where the object is released automatically after contact has some advantages over switching off the control loop manually. If a haptic force and control effort are linked, continuous control is desired to maintain stable haptic force output. Also a design in which releasing the object is integrated through the controller, is simpler and requires less concentration from the operator as he does not need to divide his attention between proper tool alignment and timing the release.

Although previous work is based on the usage of magnetic levitation as a levitation technique, it has a major limitation that only ferromagnetic objects can be handled. A handling tool based on electrostatic levitation on the other hand will allow to levitate not only conducting materials, but also semi-conductors and dielectrics. Especially in fields where contactless handling by human operators is desired, this tool can be valuable. This idea is illustrated in Fig. 1, where a human operator is picking up a silicon wafer from one location and places it on second location. He is supported by a haptic device to perform this manipulation task without failures.

In this paper, the first step to use electrostatic levitation in a contactless handling tool, is described by analyzing the Pick Up and Place behavior for such a device. Section II introduces the general principle of electrostatic levitation and its application to levitate hard disk media. The control strategy is discussed in Section III. Details of the setup and the Pick Up and Place task are described in Section IV. Finally, Section V will give some conclusions and future work.

II. ELECTROSTATIC LEVITATION

In this section, the basic principle of electrostatic levitation will be briefly discussed based on literatures [7] [8] and it is shown how it can be used to levitate a 3.5” disk from a conventional Hard Disk Drive.

A. Principle [7]

The basic principle of electrostatic levitation is schematically shown in Fig. 2. An attractive electrostatic force can be generated by creating an electric field between object and electrodes. If the overlapping area of the electrode and object is large compared to the air gap, the capacitance can be represented as

$$C = \frac{\varepsilon_0 A}{z} \tag{1}$$

and the generated electrostatic force is

$$f = \frac{\varepsilon_0 A V^2}{2z^2}, \tag{2}$$

where A is the active area, V the voltage applied to the electrode, ε_0 the permittivity of air, and z is the air gap. The minimum number of electrodes is directly related to number of the Degrees of Freedom (DOF) that need to be controlled. For n DOF a minimum of $n+1$ electrodes is necessary to control all n DOF.

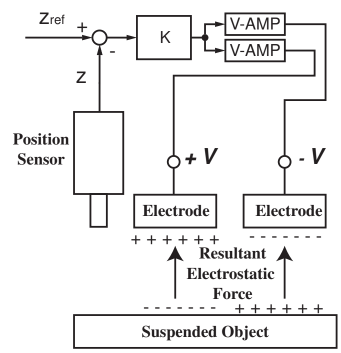


Fig. 2. Principle of electrostatic levitation for one degree of freedom

As the electrostatic force is inversely proportional to the square of the air gap, active feedback control is necessary to realize stable levitation. By applying the control voltage evenly to the positive and negative electrode, the net potential of the object remains zero and no charge accumulation occurs. This will also prevent contamination of dust particles to the object.

The force equation can be linearized around an operating point (f_e, V_e, z_e) in which for bias voltage V_e, there is an equilibrium air gap z_e where the attractive electrostatic force equals the gravity force on the object $(f_e = mg)$. With deviations from the linearization point defined as

$$z = z_e + \tilde{z}, \quad \text{and} \quad V = V_e + \tilde{V}, \tag{3}$$

this results in

$$f = K_v \tilde{V} - K_z \tilde{z} + f_e, \tag{4}$$

where

$$K_v = \frac{\varepsilon_0 A V_e}{z_e^2}, \quad K_z = \frac{\varepsilon_0 A V_e^2}{z_e^3} \quad \text{and} \quad f_e = \frac{\varepsilon_0 A V_e^2}{2z_e^2}$$

From (4) it is clear that by controlling the voltages applied to the electrodes, the air gap between object and electrodes can be regulated. For more DOF, (4) can be extended by writing it in vector and matrix form [8].

B. Levitation of Hard Disk Media [8]

The substrate material of a hard disk is conventionally aluminium. Nowadays, manufacturers also use glass composites or magnesium alloys, which both can also be levitated by electrostatic levitation. In this paper the presented work is based on a 3.5” aluminum disk that has the standardized dimensions of 95 mm outer- and 25 mm inner diameter.

The disk has 6 DOF of which only 3 DOF need active control, namely the translational vertical z-direction and the two rotational roll and pitch motions. The lateral translation motions (x, y-direction) of the disk have a passive restriction as a result of the active vertical control (z-direction) so that when the disk slips out of the central position, a restoring

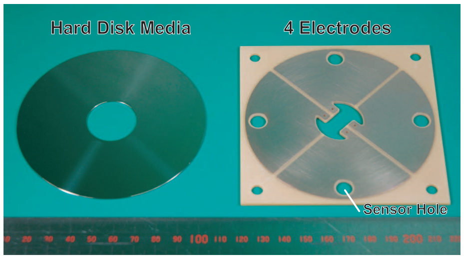


Fig. 3. Photograph of the hard disk media and the electrodes

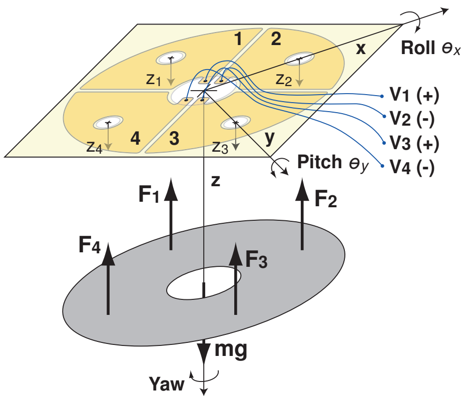


Fig. 4. Coordinate system for centralized control

force will return it [12]. This lateral restoring force however is significantly lower than the levitation force, limiting the allowable accelerations of the electrostatic levitator in the translational directions. The last rotational yaw motion is neglected due to the rotation symmetry of the disk. As a result, the disk can be levitated by a minimum of four electrodes, that are arranged in a similar disk shaped pattern as is shown in Fig. 3. In the center of each electrode there is a hole through which a displacement sensor can measure the local air gap z_i.

A coordinate system is defined in Fig. 4, where both centralized coordinates are given in terms of x, y, and z, but also for each electrode individual displacements (z_1, z_2, z_3, z_4) are given. The coordinate systems can be converted into one other by using a transformation matrix C_s:

$$\begin{bmatrix} z_c \\ \theta_x \\ \theta_y \end{bmatrix} = \underbrace{\begin{bmatrix} 1/4 & 1/4 & 1/4 & 1/4 \\ \frac{-1}{2R_s} & 0 & \frac{1}{2R_s} & 0 \\ 0 & \frac{-1}{2R_s} & 0 & \frac{1}{2R_s} \end{bmatrix}}_{C_s} \times \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \end{bmatrix}, \quad (5)$$

under the assumption that for small angles $\sin(\theta) = \theta$ and R_s is the distance from the sensor to the origin of the coordinate system.

The voltage that is sent to each electrode is a combination of the control voltage and a bias voltage, evenly distributed in two positive and two negative voltages that follows

$$V_i = (-1)^{i-1}(V_e + \tilde{V}_i), \quad (i = 1, 2, 3, 4). \quad (6)$$

It is possible to realize stable levitation of the disk with only proportional (P)-control, as there is a natural damping effect present from the air. The air gap for stable levitation is significantly smaller than the diameter of the disk and that allows the air to be modeled as a squeeze film [11]. An example of levitation by only proportional control is given in Fig. 5, where with a feedback gain of $16{\cdot}10^6$ V/m and a reference gap of 310 μm for each electrode, stable levitation is achieved.

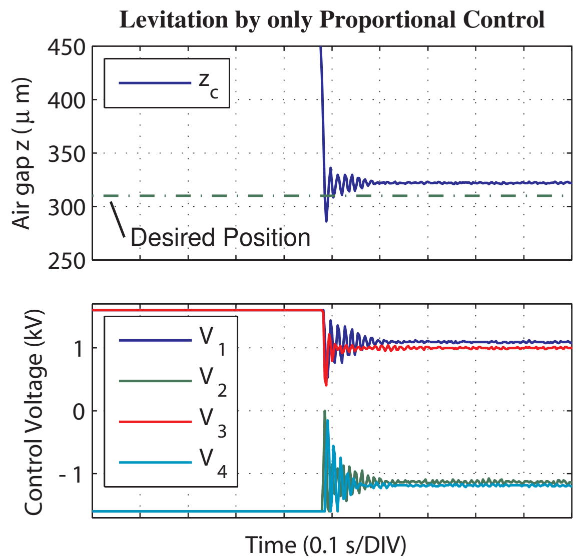


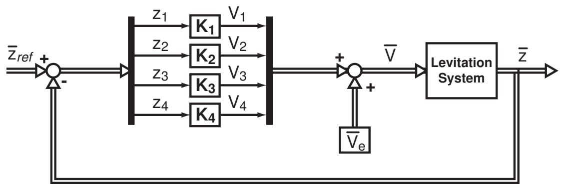
Fig. 5. Electrostatic levitation by only proportional control

III. CONTROL STRATEGY

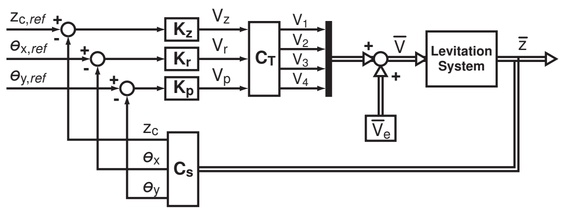
The goal of this work is to achieve a simple Pick Up and Place method that can be easily and intuitively performed by a human operator. However, to predict and understand this behavior, a linear motor is used in this paper. In a pick and place task, especially placing is difficult. To make it more easy and intuitive, an integrator can be used in the controller [13]. The effect of an integrator however can differ for various control strategies. In this section, it is first explained how automatic placing with an integral in the controller can be realized. Then, the effect of an integrator in two representative controllers, namely centralized and decentralized control, is discussed.

A. Automatic Placing

The reason for integrators in controllers is typically to converge the system to a certain state. That can be for instance convergence to a given reference position or convergence to a state where the the electrode voltages are exactly the bias voltages. However, an integrator in the controller also allows to release or place a contactless levitated object automatically. In the placing task, the electrostatic levitator moves down with a stable levitated disk. At the moment of contact at the desired location, a position error is forced resulting from a smaller air gap. The controller will make an effort to restore the state of the disk, i.e. to increase the air gap again. With an integrator in the controller, this effort will grow exponentially with time. If after some time, the



(a) De-centralized control



(b) Centralized control

Fig. 6. Two control approaches for levitation

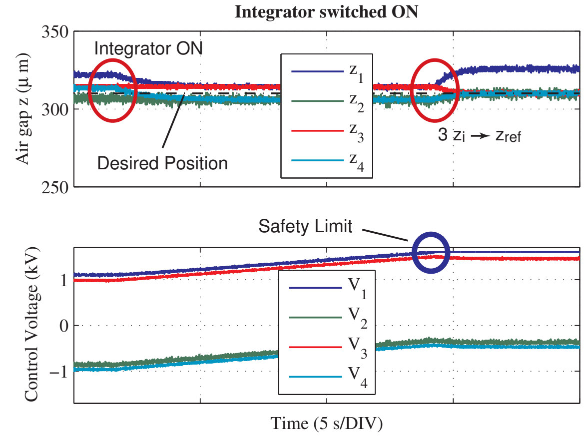


Fig. 7. Switching on integrator in de-centralized control

levitator is moved up again, the resultant force on the disk is still downward. If this is still the case when the maximum air gap of levitation is reached, placing is realized. It requires no command from the operator, so he can focus his attention on placing at the accurate location, while the release is realized automatically.

B. De-Centralized Control

A basic way to realize levitation of the disk is to apply de-centralized control. It allows to tune the controller settings for only one electrode and duplicate the settings for the other electrodes as they should be identical. De-centralized control is schematically shown in Fig. 6(a), where the controllers K_1, K_2, K_3, and K_4 can be the same.

If the controller is only a Proportional Derivative (PD)-controller, no problem occurs for realizing stable levitation. However, when an integrator is added in for instance PID-control, the system will become unstable. The reason for this is that three degrees of freedom are controlled by four controllers. The number of electrodes cannot be reduced because three DOF need a minimum of four electrodes. That means that if the system does not consist of four perfect identical electrode- and sensor combinations, which is in practice always the case, there is an error that will be increased by the integrator. An example is shown in Fig. 7, where an integrator (in PID-control) is switched ON during stable levitation. It can be seen that the controller is unable to bring each air gap for each electrode to the desired position. As a result, the integrator and the position error increases the control voltage for each electrode. As a safety precaution to prevent sparking, the maximum allowable control voltage is limited and when this value is reached for one electrode (V_1), the system is no longer actively controlled by four controllers, so the air gap for the other electrodes converge to the desired air gap. So even if this state is not really unstable, it is still undesired as the voltage of two electrodes is very high, increasing the chance of sparking. Plus the positive and negative voltage are no longer distributed evenly, which means the disk is no longer at zero potential and can attract dust particles.

In conclusion this means that the integrator cannot be used for de-centralized control making it less suitable for the pick and place task.

C. Centralized Control

In centralized control, there are only three controllers to control all three DOF. However, the number of electrodes and sensors is unchanged and only a transformation on the position signals is performed as was shown in (5). A graphical representation is given in Fig. 6(b). Here, K_z is the controller for the air gap of the center of the disk z_c, controller K_r controls the roll, and K_p the pitch of the disk. To transform the control voltages in correct electrode voltages, a similar inverse transformation has to be performed:

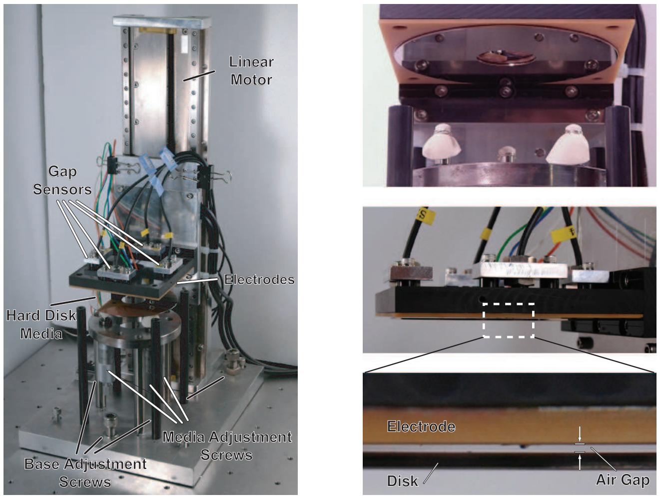
$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} = \underbrace{\begin{bmatrix} 1/4 & 1/2 & 0 \\ -1/4 & 0 & -1/2 \\ 1/4 & -1/2 & 0 \\ -1/4 & 0 & 1/2 \end{bmatrix}}_{C_T} \times \begin{bmatrix} V_z \\ V_r \\ V_p \end{bmatrix}, \quad (7)$$

where in C_T it can be seen that for the vertical motion, the voltage is equally distributed over the four electrodes (observing polarity). For the two rotation motions, only two electrodes are utilized for each mode, which is a result of the definition of the coordinate system (Fig. 4).

PID-control on the center air gap of the disk z_c causes now no longer the problems encountered at de-centralized control. When the integrator is switched on, the central position of the disk will converge to the desired reference position, without continuous increasing of the electrode voltages.

IV. EXPERIMENTAL WORK

In this section the details of the experimental setup will be described in more detail. Furthermore, results are presented of the actual Pick Up and Place task by evaluating the air gap and electrode voltages.



(a) Photograph of Setup (b) Stable Levitation

Fig. 8. Details of Experimental setup

A. Experimental Setup

The experimental setup consists of two main components, namely the electrostatic levitator and a linear motor (IKO LT100CGS-200/10) to provide a controllable pick and place motion. A photo of the setup is shown in Fig. 8(a).

The electrodes are manufactured on a standard printed circuit board by removing the undesired areas through milling. The electrodes are then polished and electrically connected. An insulating film (thickness of 60 μm) is adhered to the surface of the electrode to avoid direct contact between the disk and the electrode and to reduce dust particles on the disk [14]. The electrodes are separated by a 2 mm wide insulating gutter zone and the corners are rounded off to prevent charge concentration. The electrodes are adhered to a bakelite back plate (100 mm $\times$ 100 mm $\times$ 10 mm) to prevent bending of the electrodes and to support the air gap displacement sensors. It also connects the electrostatic levitator to the linear motor.

The eddy-current displacements sensors (Keyence EX-800) have a sensing range of 0 to 1 mm with a sensitivity of 5 mV/μm and are placed at a radius of 41 mm from the center of the coordinate system.

The aluminium hard disk has a thickness of 0.82 mm and weighs 14.42 g. The disk is initially placed on three micrometer positioning screws (Media Adjustment Screws), which are electrically isolated at the tip. With these adjustment screws the initial air gap and orientation of the disk can be regulated. To control the orientation of the whole setup, three Base Adjustment Screws supports the base plate of the setup.

The centralized controller is implemented in a digital signal processing (DSP) system running at 3.3 kHz. The controller output is connected to four high voltage D.C. amplifiers (Trek 609C-6), which have an internal gain of 1000 and their output is limited at 1.6 kV in absolute value. The controller gains are given in Table I.

TABLE I
CONTROL SETTINGS

Proportional gain	$K_P, \quad z_c$	$16 \cdot 10^6$ V/m
	$K_P, \quad \theta_x, \theta_y$	$4.2 \cdot 10^5$ V/rad
Derivative gain	$K_D, \quad z_c$	$0.16 \cdot 10^6$ (V s)/m
	$K_D, \quad \theta_x, \theta_y$	0
Integral gain	$K_I, \quad z_c$	$10 \cdot 10^6$ V/(m s)
	$K_I, \quad \theta_x, \theta_y$	0
Bias Voltage	V_e	910 V
Reference setpoint	$z_{c,ref}$	310 μm
	$\theta_{x,ref}, \theta_{y,ref}$	0

Photos of stable levitation are shown in Fig. 8(b), where the hard disk is suspended with a $\approx$ 300 μm air gap. The hard disk can be picked up and placed by moving the linear motor up and down as will be described in details in the next section. With a motion profile that is sent to the linear motor, the downward speed, upward speed, contact time and the lowest position of the linear motor can be controlled. In these experiments, the speed of motion is set to 7.5 mm/s. When the linear motor is in its zero position, the air gap with the disk is about 250 μm.

B. Experimental Results

1) Pick Up: In order to pick up the hard disk, only PD-control is used to prevent unwanted voltage wind up from the integrator. Details of the Pick Up are given in Fig. 9. The linear motor will move down until it reaches the 0.1 mm position, where the air gap would be around 350 μm if there was no voltage on the electrodes. Instead, the disk jumps directly to the desired position and only when the linear motor moves up again after 0.5 s, a small disturbance can be seen in position of the disk. Note that for safety reasons, the control voltage is only switched on automatically the moment the disk comes into sensing range.

2) Place: Details of the Place task are shown in Fig. 10. The linear motor moves down while the disk is at the desired reference air gap controlled by a PID-controller. From the moment of contact, a position error of about 60 μm is forced as the linear motor stays at its zero position. If there was only PD-control, the control voltages would remain constant during this holding time as they are direct proportional to the air gap error. With PID-control however, the integrator will reduce the control voltages (in absolute value) with time. Even when the linear motor moves up again and the air gap increases again, it takes time for the controller to "recover" stable levitation and it is unable to re-levitate the disk. As a result, the disk remains on the media adjustment screws and placing was successful. In this experiment the holding time is relatively long, but this can be considerably reduced by increasing the integral controller gain or increase the position error (without instability of course). For a human operator assisted by a haptic device this automatic placing can be more intuitive as the haptic device will give a force proportional to the controller effort,

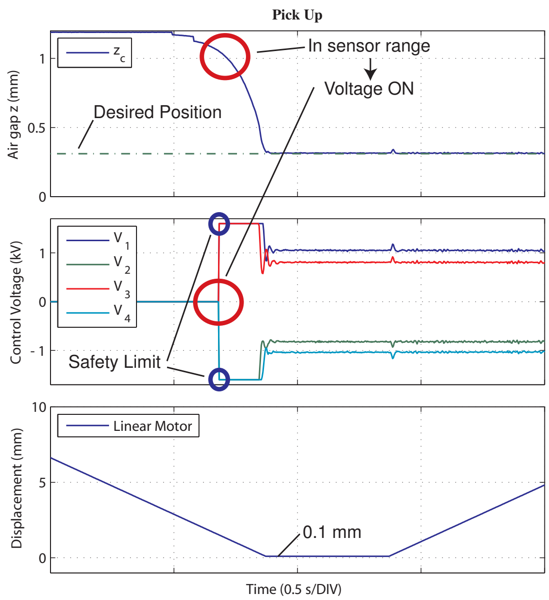


Fig. 9. Details of Pick Up task

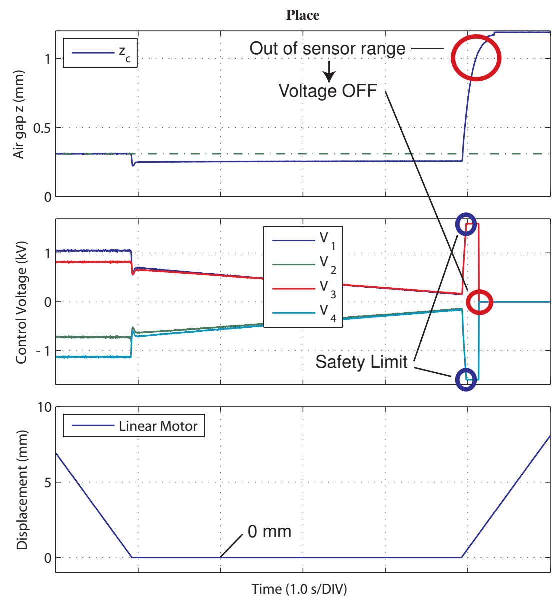


Fig. 10. Details of Place task

so the increasing controller effort (in experiment leading to reduction of control voltage) will mean an increasing repulsive (upwards) force from the haptic device, indicating by force sensation that placing was successful.

V. CONCLUSIONS AND FUTURE WORKS

A. Conclusions

In this paper the object handling tasks of Pick Up and Place with electrostatic levitation have been discussed. These tasks are essential to realize an object handling tool that allows human operators to handle intuitively contact-sensitive objects such as silicon wafers or hard disk media without mechanical contact. It was shown that an integrator in the controller is important to realize an automatic release of the object in the Place task. However, an integrator in the controller is unstable for de-centralized control due to the over constraining of three degrees of freedom by four controllers. Thus, centralized control in which there are only three controllers, is used for the Pick and Place task. Experimental results show a stable Pick Up and Place motion of a hard disk media, which has a steady state air gap of about 300 μm. The results are promising for the development of the contactless object handling tool and will contribute to easy and intuitive contactless object handling.

B. Future Works

The most important next step in the development of the contactless object handling tool based on electrostatic levitation, will be the replacement of the linear motor by a haptic device and perform Pick and Place tasks by human operators. Some design requirements for the haptic device will be a high stiffness in the vertical direction, a force large enough to counteract motion and forces induced by the human operator and a workspace large enough for manipulation. It would be interesting to consider a mobile variant haptic device to further extend the global workspace of such a tool.

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