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Using Tilt-Control in Non-Contact Manipulation Systems: Development of 2-DOF Tilting Actuator with Remote Center of Rotation

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***Abstract*— Levitation systems allow delicate objects to be handled without contact by actively controlling a levitation force that suspends the object. A drawback of levitation systems for thin objects is that the *lateral* force can not be controlled actively and is much weaker than the levitation force. This is a problem for non-contact manipulation systems as the object may loose its alignment with the levitator (and drop) because of the inertial forces coming from the lateral accelerations. In earlier work, a solution was proposed using *Tilt Control* in which lateral accelerations are compensated by the levitation force by tilting both the object and the levitator. This concept has been verified in an experimental setup that was capable of tilting around only one axis. In this paper, a new and unique design is presented of a tilting actuator that is capable of rotating around two axis, so that full 3D-space manipulation is possible. A key aspect of the Tilt Control strategy is that the center of rotation is at the center of mass of the levitated object and, for the tilting actuator, this means that it should have a remote center of rotation. A spherical cap or dome-shaped structure supported by three ball bearings, is used as the fundamental principle for the tilting actuator design as it has a natural remote center. The design and realization of this tilting actuator are described in this paper and a pilot experiment was carried out in which the tilting actuator, with a magnetic levitator installed, was attached to a linear motor. The results showed successful tilting action as relative lateral motion of the levitated object were significantly reduced on two axis.**

I. INTRODUCTION

Using levitation techniques for handling contact-sensitive objects can be beneficial because the absence of mechanical contact between the levitator and the handled object. Several negative effects such as contamination [1] and contact-damage can be avoided by using these non-contact handling techniques. For objects such as silicon wafers, glass plates of Flat Panel Displays, or sheet metal, this can be vital for realizing high quality end-products. Examples of such levitation techniques are: (1) magnetic levitation [2], that can be used for ferromagnetic objects; (2) electrostatic levitation that can handle a more wider range of materials such as conductors, semiconductors, and even dielectrics like glass [3]–[5].

In these levitation systems, the levitator provides the "holding" levitation force to compensate for gravitational, inertial, and external forces by maintaining the object at a certain distance (air gap) from the levitator. The levitation force is actively controlled using a feedback control loop on the measured gap between the levitator and the object, which realizes a positive stiffness for the suspended object. For controlling multiple Degrees Of Freedom (DOF) of the object, multiple actuators have to be placed strategically around the object. However, it is not always necessary to control all six DOF of a rigid object with active control, as often a passive restoring force is present that naturally stabilizes some of the DOF. Stable levitation of thin disk-shaped objects, for example, is possible by controlling only the vertical gap, the roll, and the pitch rotations [4], [6]. The lateral motions of the disk are stabilized by a *passive* force, that keeps the object aligned with the levitator where the potential is the highest [7]. This lateral restoring force is far weaker (roughly a thousand times) than the controlled levitation force and it can not be enhanced by means of control, because the side area of the object is too small for additional actuators to act upon. This weak force poses limitations in a non-contact manipulation system as horizontal accelerations have to be restrained to prevent loosing the object.

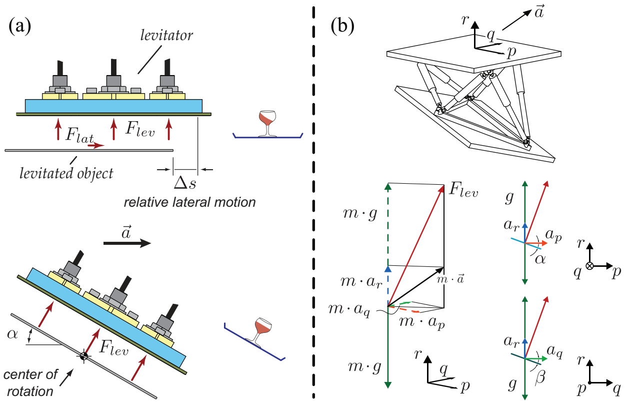

Fig. 1. Tilt Control: (a) tilting eliminates lateral forces and thus relative lateral displacement Δs, (b) geometric relationships for a 3D acceleration $\vec{a}$ needing two tilting angles α and β

A solution of *Tilt Control* has been proposed in previous work [6], [8], which works similar to the technique waiters use in restaurants to serve beverages quickly and without spilling the content, and it is illustrated in Fig. 1(a). Key-aspects of this strategy are: (1) the tilting control is implemented in a feed-forward approach, such that sensing of the relative lateral position is not required; (2) the axis of rotation is at the center of mass of the object, minimizing disturbances to the levitated object. Significant improvements in allowable horizontal accelerations were realized by using this technique in both magnetic levitation and electrostatic levitation systems. However, the experimental work was limited to only *one* tilting angle, which will not be sufficient for a non-contact manipulation system that will be used in 3D-space as it requires two tilting angles as shown in Fig. 1(b).

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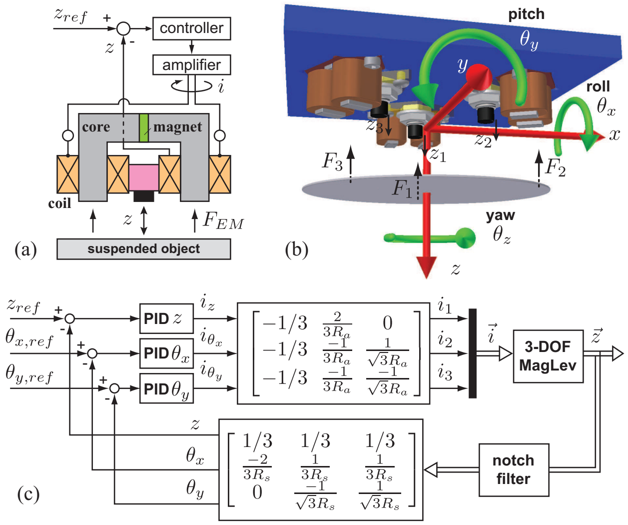

Fig. 2. Magnetic levitation

In this paper, a new tilting actuator is described that realizes tilting of two DOF *with* a remote center of rotation. The actuator has been developed specific for the non-contact handling task and uses only two actuators with a nearly equal workload. The design is made in such a way that the type of levitators can be changed between magnetic levitation and electrostatic levitation and that there are no mechanical parts below the levitator. The result is a unique design that is relatively compact and can be mounted as an end-effector to, for example, a robotic manipulator. However, only the magnetic levitator has been realized so far for the newly designed tilting actuator and the realization of the electrostatic levitator is still future work. Therefore, electrostatic levitation will not be discussed in this paper.

II. LEVITATION SYSTEM & TILT CONTROL

Since both the magnetic levitation system and the tilt control concept have been described in previous work, this section only describes their essential aspects that are necessary for understanding the work presented in this paper.

The principle of magnetic levitation is shown in Fig. 2(a). The attractive electromagnetic force F_{EM} is generated in a magnetic circuit through a coil current i and by a permanent magnet. Stable levitation is possible by controlling the current through the coils based on the measured air gap z between the magnetic actuator and the object. A simple PID-controller is sufficient to realize levitation and the object appears to be suspended by an invisible spring with stiffness k_{lev}. For the levitation of a disk-shaped object, three magnetic actuators can be equally distributed around the central axis with a radius R_a, as is shown in Fig. 2(b). To measure the position of the object, three gap sensors are also equally distributed around the same central axis but with a radius R_s. They measure the air gap in local coordinates z_i, $(i = 1, 2, 3)$. With a decentralized controller structure, as shown in Fig. 2(c), three DOF are independently and actively controlled: the air gap z, the roll θ_x, and the pitch θ_y. As both the actuators and the sensors are in local coordinates, two transformation matrices are used in this controller structure to transform these local coordinates. It assumes that the relative tilting angles of the object with respect to the levitator are small $(\sin(\theta) \approx \theta)$. A notch filter is used on the gap signals to suppress the first resonance mode of the disk-shaped object. The yaw rotation θ_z is uncontrolled because it is rotation symmetric. The lateral $x-$, and $y-$motion are passive stable as a restoring force occurs when the object moves out of the central position. The reason of tilt control is the weakness of this lateral restoring force and a measurement of stiffness shows that is far weaker than the levitation force (measured values):

levitation stiffness: $k_{lev} = 3.4$ kN/m
lateral stiffness: $k_{lat} = 2.5$ N/m

In the tilt control strategy, both the levitator and the object are tilted during lateral accelerations. This has the advantage that larger tilting angles and thus larger allowable lateral accelerations can be realized than by tilting of only the object by the levitation controller. Other researchers have also implemented tilting strategies in non-contact handling systems, but those systems require sensing of the relative lateral position as the tilting is realized by a feedback loop on this position signal [9], [10]. Furthermore, the axis of rotation in their design is not at the center of mass of the object, which introduces disturbances to the levitated object at the instant of tilting. In the Tilt Control strategy used in this paper, the tilting action is based on a feed-forward control action, which means that in real-time, the tilting angles are computed from the acceleration/velocity/position-signal that is sent to the position actuators. By setting the center of rotation at the center of mass of the object, the disturbances to the object are minimized *and* the center of the object does not move relatively to the frame that holds the tilting mechanism.

The Tilt Control strategy for levitation systems uses the fact that the levitation force is much stronger than the lateral restoring force. By tilting both the levitator and the object, only the levitation force is used for compensating the gravitational force *and* the inertial forces coming from the acceleration. As can be seen in Fig. 1(b), the tilting angles follow simple geometric relations and the levitation force has to increase:

$$\alpha = \arctan\left(\frac{a_p}{a_r + g}\right) \tag{1}$$

$$\beta = \arctan\left(\frac{a_q}{a_r + g}\right) \tag{2}$$

$$F_{lev} = m\sqrt{a_p^2 + a_q^2 + (a_r + g)^2} \tag{3}$$

The only limitation to this strategy is that the levitation force can not be increased indefinitely, because in practice, the current going through the coils should not be too high. However, the tilting angles that can be realized at the maximum levitation force will exceed the maximum tilting angle of the tilting actuator, such that this limitation is insignificant.

III. DESIGN AND REALIZATION OF TILT ACTUATOR

A. *Design requirements*

For the design of the tilting actuator, the following design requirements were used:

- Remote center of rotation
- Compact and relatively lightweight
- Maximum angle rotation of ± 10°
- Levitator should be inter-exchangeable (magnetic and electrostatic)

The reason for having a remote center of rotation at the center of mass of the levitated object has already been described in the tilt concept. As the tilting actuator and levitator are to be attached as an end-effector to a robotic manipulator, it should be an objective to minimize the size and weight of this structure. If the required angle rotations are very large, the mechanism to realize this will become more bulky. Therefore, the maximum tilting angles are limited to ± 10° as a trade-off, which will allow for horizontal accelerations up to 1.7 m/s^2. In earlier work which used only one tilting angle, the tilting angle did not exceed 6° so that the requirements for the new design should be sufficient. Lastly, the design of the tilting actuator should be made in such a way that the levitator itself can be easily exchanged between the magnetic levitator and an electrostatic levitator. As the magnetic levitator takes up more space than the electrostatic levitator, the geometric size and structure of most parts will be decided based on the magnetic levitator installed.

B. *2-DOF remote center of rotation*

The one-DOF rotational actuator that was realized in previous work was based on rotational bearings and a DC-motor with a friction-drive transmission. If a new design for two-DOF is made using the same principle, the result would be a gimbal structure. Such a design has three major disadvantages: (1) it will be very bulky and heavy, (2) the load for the rotational actuators is unequal, and (3) the bearings and their supporting structure will be below the levitator, which can be obstructive in the manipulation task. Another solution could be the use of a parallel mechanism actuator such as the Stewart platform, which has six DOF and is therefore capable of rotation around a remote center. However, these devices can be very expensive, bulky, and may need more than two actuator/sensor units for their operation.

In this paper, a new device is introduced that realizes two DOF tilting rotations by using a geometry that has a natural remote center of rotation: a spherical cap. A spherical cap or dome is the portion of a hollow sphere that remains if the sphere is cut along a plane, as shown in Fig. 3. By supporting the inner surface by three ball bearings, all the translational DOF are constraint and only rotational DOF at the indicated center remain. The space between the center of rotation and the spherical cap can be used to place the supporting structure for the bearings *and* to house the levitator that has to be *above* the center of rotation. The video also shows how this concept is transformed in the design using CAD animations.

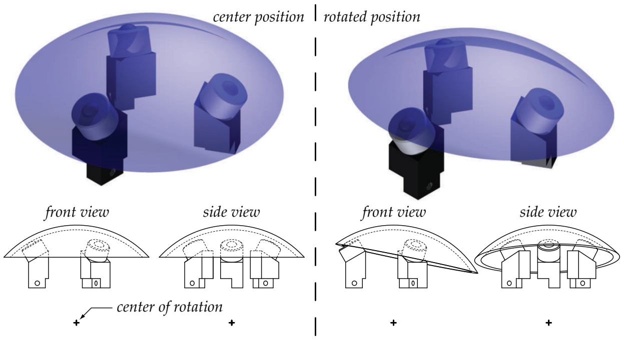

Fig. 3. A spherical cap supported by three ball bearings has only three rotational DOF

A drawback of this design is that the dome has to be specially made and that conventional actuators to directly drive the DOF are not available. Another concern is that one of the rotational DOF, namely the yaw rotation around the vertical axis, has to be suppressed. In this design, linear motion of two actuators is transformed in the desired rotational motion ($x, y \rightarrow \theta_y, \theta_x$) by using a universal joint as a transmission that is attached to the top of the sphere. A ball spline bearing can suppress the yaw rotation and allow for small vertical translation that will occur when there is a rotation. A pre-load mechanism will, together with the own weight of dome and levitator, keep the dome pressed to the bearings.

C. *Total design*

The whole design is shown in Fig. 4 in an exploded view so that all components are clearly visible. The design has the following critical parts which are described from top to bottom:

- Linear XY-drive structure with main actuators and a pre-load mechanism
- Ball spline bearing and universal joint that transforms translational into rotational motion
- Dome structure to which levitator and lateral sensors will be attached (rotational part)
- Main stationary support that holds the bearings supporting the dome, levitator and an angle sensor
- Levitator which can be either magnetic or electrostatic and also holds part of the angle sensor
- The angle sensor, consisting of a two-dimensional position sensitive diode (PSD) and laser diode
- Four lateral position sensors that can be attached to the side of the dome for performance evaluation

The design of many of these components is interlinked as they have to be connected to each other or they are in a close proximity with each other. The components will be described in logical order, starting with the dome structure

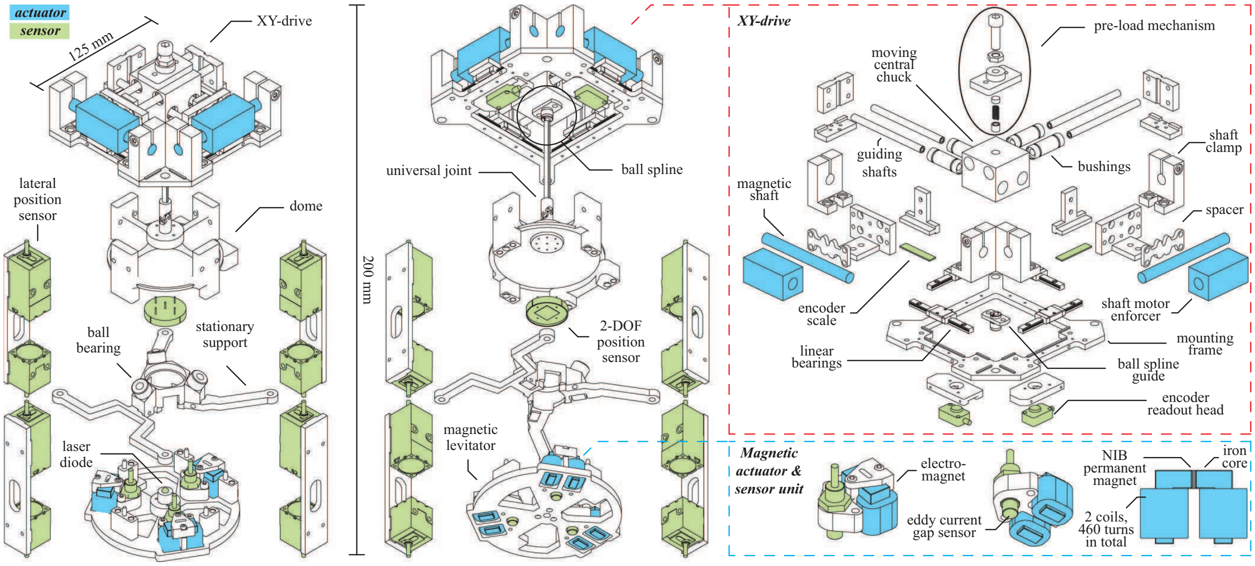

Fig. 4. Design of two-DOF rotational actuator shown with magnetic levitator. Additional details on the XY-drive and the magnetic actuator/sensor unit

1) Dome structure: The main size of the dome-shaped structure is dictated by the levitator and levitated object, which is 100 mm in diameter. With an inner dome radius of 50 mm, there is just enough space to house all the other components and provide enough inner surface for the ball bearings. The material used for the dome is MC-Nylon and CNC-machining is used for the manufacturing. At the top of the dome, both the outer and the inner surface is flattened for mounting the universal joint. The bottom of the dome has four protruding support legs to which the levitator will be attached. To realize a good and accurate connection between the dome and the levitator, placement pins/bushings and small permanent magnets are used. These supporting legs also fulfill another function as lateral position sensors can be attached to them when the performance of the device has to be evaluated.

2) Stationary support for bearings and angle sensor: As the dome and levitator are the moving parts, the bearings that support them has to be stationary. Contact should only occur at the interaction point of the dome with the bearings. Three ball bearings (Freebear C-2H) are radially distributed along the cental vertical axis at an angle of 30° with that axis. To avoid contact with the dome and the levitator, this support has a unique shape as can be seen in Fig. 4. To provide enough stiffness, this support is made out of aluminium. A two DOF position sensitive detector (PSD) is attached in the center to this support (Hamamatsu S1880) and it has an active sensitive area of 12 mm×12 mm. An infrared laser diode (Hamamatsu L1915) will be fixed to the levitator with the radiation axis going through the center of rotation. By using a signal processing circuit (Hamamatsu C4674), two analogue voltages can be measured which represent an $\{x, y\}$-position of the laser spot, from which the tilting angles can be determined. The distance of the PSD to the center of rotation is 35 mm, such that tilting angles up to $\pm 10^\circ$ can be measured.

3) Magnetic levitator: The magnetic levitator is almost identical to the one used in previous work. Three magnetic actuator and sensor units, shown in detail in Fig. 4, are radially distributed around the central axis with $R_a = 40$ mm and $R_s = 24$ mm. The nominal air gap between the magnetic actuators and the iron disk is 3 mm, so the gap sensors (Keyence EX-008), which have a measurement range of 0 mm to 2 mm, are 2 mm closer to the object in order for the object to be in the middle of the sensor range during nominal levitation. The supporting frame that holds these actuator and sensor units is designed in order to maintain these distances and have the sensor and actuator just stick out of the bottom surface. Bakelite is used as the basic material as it is relatively strong, lightweight, and easy to machine. In the center, the laser diode that is used for the angle measurement, is attached to this frame. Furthermore, the lateral sensors require a round edge of this supporting frame that has the same radius as the disk, which explains the outer shape of this structure. Some excess material has been removed to reduce weight and increase the airflow around the magnetic coils.

4) XY-drive: The details of the XY-drive design is shown in Fig. 4. The linear position actuators used in this design are shaft motors (Nippon Pulse Motor S080) that have a relatively large stroke and a high output force, 25 mm and 7.2 N respectively. The selected amplifiers (Panasonic MINAS A4L) can directly control the force of the motors by an analogue voltage input, which has the advantage that the controller can be designed in-house. Four linear bearings (IKO LWL5) are used to guide the enforcers of the shaft motor. As the shaft motors require an encoder signal to function, two optical encoders (MicroE, Mercury M2000) are installed which have a set resolution of 0.1 μm. To realize an equal workload for each actuator, the two shaft motors are positioned orthogonal to each other, which also means the rotations are completely independent. The motion of the two actuators is transferred by a central moving chuck to which the ball spline bearing is fixed. A pre-load mechanism is also attached to this chuck with which the dome is pressed to the supporting ball bearings.

5) Lateral sensors: Four lateral sensors (Omron ZX-LT010) can be attached to the dome structure to measure the lateral position of the object. This is only done for evaluation purposes and they are *not* required for the tilting operation. These optical sensors use an parallel laser beam with an active area of 1 mm ×10 mm and measure the position by measuring the amount of laser light that is blocked by the levitated object. When the object is perfectly aligned with the levitator, which has the same radius at the location of the sensors, the output of the lateral sensors is zero. With this configuration, not all relative $\{x, y\}$-positions can be measured exclusively as small dead-zone areas exist, but for evaluation purposes, this is acceptable.

6) Realization: The realization of the described design is shown in Fig. 5, with several of the subsystem depicted individually. In Fig. 5(a) the whole two-DOF tilting setup with magnetic levitator is attached to a linear motor that is used for the pilot experiment. The same photo also shows an additional (transparent) protection rail that should protect the tilting mechanism and levitator in case of some unexpected failure. Also, the signal processing board of the PSD is visible on the right side, which has to be close to the PSD to reduce noise. Fig. 5(b) shows a close up of the linear drive actuators with the pre-load mechanism and Fig. 5(c) shows the stationary support which holds the three bearings and the PSD. The dome with the attachment bushings and magnets is shown in Fig. 5(d). Finally, details of the levitator are shown in Fig. 5(e) and (f).

Several problems were encountered during the realization of this prototype. The universal joint has undesirable play which is a cause of inaccuracy for the tilting angles. Using the angle sensor as the feedback sensor can partly compensate for this, however, errors in the yaw-rotation can not be compensated. Replacing the universal joint with a flexure joint that has two coincident axis of rotation can solve this problem and should be considered for future prototypes. Furthermore, the drivers of the shaft motor produce significant noise which influences the servo behavior of the tilting controllers. Both angle sensor and the Digital Signal Processor pick up noise for the shaft motor with undesired results. This negative effect can be partly reduced by extensive shielding, grounding and using ferrite cores on all signal carriers.

IV. EXPERIMENT

Two basic experiments are carried out to evaluate the tilting actuator. The first experiment evaluates *only* the tracking behavior of both tilting angles without any levitation or motion from the linear motor. In the second experiment, the tilting action is evaluated with one-DOF motion of the linear motion and with active levitation.

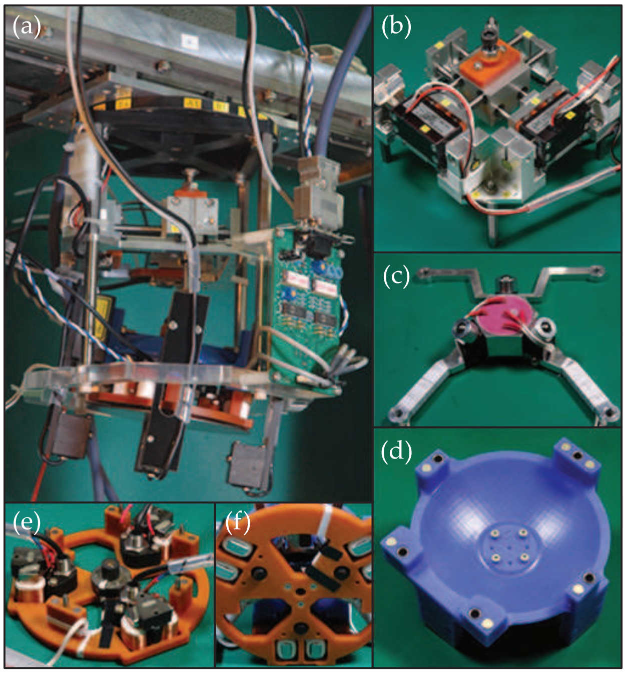

Fig. 5. (a) Realization of 2-DOF tilting actuator shown with magnetic levitator. (b) XY linear drive unit. (c) Stationary support with bearings and PSD sensor. (d) Spherical cap or dome. (e) magnetic levitator - top view. (f) magnetic levitator - bottom view.

A. Servo behavior

The tilting actuators are controlled by a PID-controller for each angle with the following gains: $K_P = 40$ N/deg, $K_D = 0.4$ N s/deg, and $K_I = 40$ N/s deg based on the measured angle from the PSD angle sensor. The performance is evaluated by two different reference signals: (1) ramp-shaped signal that has been used in previous work and that will also be used in the second experiment, (2) sinusoidal signal with a relative phase shift of 90° between the α and β actuator. The sinusoidal reference signals will create a tilting motion such that the moving chuck in the XY-drive unit describes a circular motion (also shown in the video).

The results for the ramp-shaped signal are shown in Fig. 6(a), where both the α-actuator and the β-actuator received the same signal. The measured angles follow the reference value fairly accurate. The angle errors which are in the order of $0.1°$ are acceptable for this application. The results of the sinusoidal reference signal are shown in Fig. 6(b) and they are very similar. It can be concluded, that the performance of two-DOF tilting actuator is sufficient for the non-contact manipulation task.

B. Tilting during 1-DOF acceleration

In the second experiment, the tilting actuator with a levitated sheet metal disk will be moved by the linear motor and has accelerations along one axis. To ensure that tilting in both angles is required, the tilting mechanism is attached to the linear motor with a certain orientation angle γ as is shown in Fig. 7. The acceleration profile will generate a third-order smooth motion profile for the

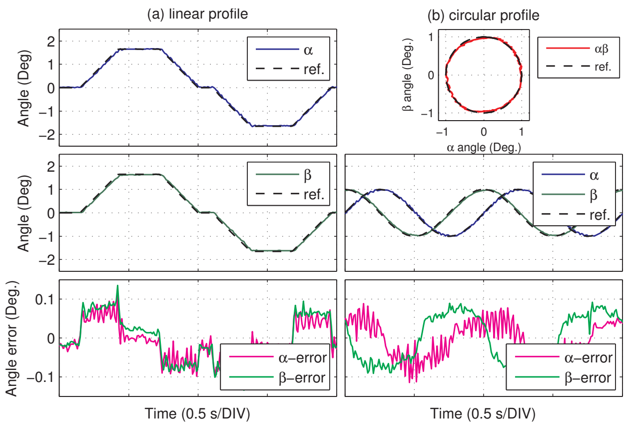

Fig. 6. Servo behavior for both an acceleration profile and a circular motion

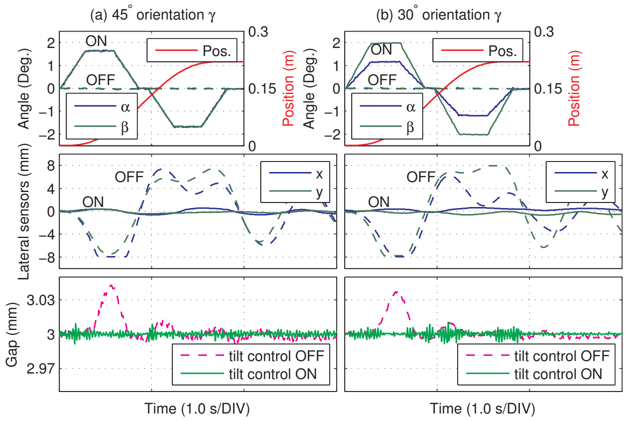

Fig. 8. Tilting while the setup is under different angles

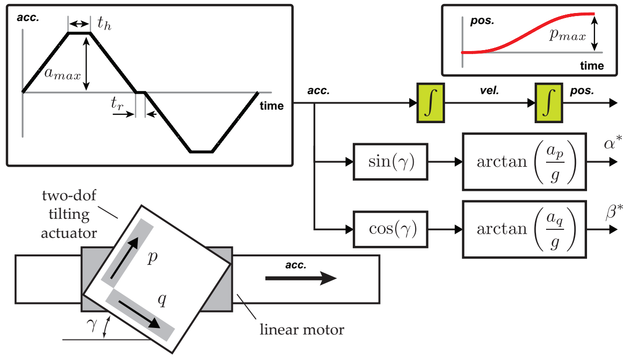

Fig. 7. Conditions for experiment

linear motor to follow and it has the following parameters: $a_{max} = 0.4$ m/s^2, $t_h = 0.3$ s, $t_r = 0.1$ s, $p_{max} = 0.22$ m. The acceleration is decomposed to local components a_p and a_q from which the reference tilting angles α^* and β^* are calculated using (1) and (2). The experiment is carried out with tilt control *OFF* and *ON* for two different orientation angles: $\gamma = 45°$, where the load for each actuator is equal; $\gamma = 30°$, where the load for the p-direction is lower. The performance can be evaluated by the relative lateral motion (slip) of the object with respect to the levitator, which is recorded for each direction by a pair of lateral sensors.

The results are shown in Fig. 8 and in both cases, the relative lateral motion of x and y are significantly reduced by the tilting action, which means that the disk stays aligned with the levitator. It also shows that there is hardly any effect of the orientation angle γ on the performance. The gap information z of the disk also confirms that during the tilting action, the disturbance to the levitated disk is much smaller.

V. CONCLUSIONS AND FUTURE WORK

The implementation of levitation systems for non-contact handling systems is limited by the restricted lateral restoring force. Planar accelerations have to be limited to avoid levitation failure and loosing the object. *Tilt Control* compensates for this drawback by using the levitation force to not only balance the gravitational, but also the inertial forces. Previous work has shown the significance of this strategy with a one-DOF tilting experimental setup. A new two-DOF tilting actuator has been presented in this paper that realizes tilting around a remote center by using a dome-shaped structure supported by ball bearings. The rotational angles are driven by two un-coupled linear shaft motors through a universal joint and a ball-spline bearing. Initial experiments revealed that the servo-behavior for two rotational angles is sufficient for a non-contact manipulation task. This is verified by the same acceleration experiment that was used in previous work, but where the tilting actuator is placed at a different orientation angle, such that both tilting angles need to be actuated. The results show the significant contribution of tilt control and confirms the two-DOF tilting actuator is operating satisfactory. The main future work will be the evaluation of this setup in a 3D-manipulation task, which is currently under development.

REFERENCES

[1] J. O'Hanlon, "Advances in vacuum contamination control for electronic materials processing," *J. Vac. Sci. Technol. A*, vol. 5, no. 4, pp. 2067–72, Jul. 1987.

[2] T. Nakagawa, M. Hama, and T. Furukawa, "Study of magnetic levitation technique applied to steel plate production line," *IEEE Trans. Magn.*, vol. 36, no. 5, pp. 3686–89, Sep. 2000.

[3] J. U. Jeon and T. Higuchi, "Electrostatic suspension of dielectrics," *IEEE Trans. Ind. Electron.*, vol. 45, no. 6, pp. 938–46, Dec. 1998.

[4] J. Jin, T. Higuchi, and M. Kanemoto, "Electrostatic levitator for hard disk media," *IEEE Trans. Ind. Electron.*, vol. 42, no. 5, pp. 467–73, Oct. 1995.

[5] ——, "Electrostatic silicon wafer suspension," in *4th Int. Symp. Magnetic Bearings*, ETH Zurich, 1994, pp. 343–48.

[6] E. van West, A. Yamamoto, and T. Higuchi, "Manipulation of thin objects using levitation techniques, tilt control, and haptics," *Trans. Autom. Sci. Eng.*, in press, 2009.

[7] S. J. Woo, J. U. Jeon, T. Higuchi, and J. Jin, "Electrostatic force analysis of electrostatic levitation system," in *Proc. 34th SICE Annu. Conf.*, Hokkaido, Japan, 1995, pp. 1347–52.

[8] E. van West, A. Yamamoto, and T. Higuchi, "Transportation of hard disk media using electrostatic levitation and tilt control," in *Proc. IEEE ICRA'08*, Pasadena, 2008, pp. 755–760.

[9] A.-S. Koh, R. Ford, and T. Seshadri, "Wafer handling with levitation," *J. Electron. Manuf.*, vol. 2, no. 3, pp. 101–7, Sep. 1992.

[10] M. Morishita and M. Akashi, "A gravity compliant guide system for magnetically levitated plates," in *Technical Meeting on Linear Drive, IEE Japan*, no. LD-98-36, Apr. 1998, pp. 37–42.