35

Using Haptic Technology to Improve Non-Contact Handling: the "Haptic Tweezer" Concept

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1. Introduction

This chapter describes the concept named "Haptic Tweezer," which is in essence an object handling tool for contact-sensitive objects that are handled without any mechanical contact between the tool and the object, *with* the help of haptic technology. By combining haptic technology with conventional levitation systems, such as magnetic levitation and electrostatic levitation, intuitive and reliable non-contact object handling can be realized. This work has been previously published in journal and conference articles (van West, Yamamoto, Burns & Higuchi, 2007; van West, Yamamoto & Higuchi, 2007a;b) which form the basis of the information presented in this chapter.

Levitation techniques are very suitable for handling contact-sensitive objects because of the absence of mechanical contact between the levitator and the levitated object. Several negative effects such as contamination, contact damage, and stiction (Bhushan, 2003; Rollot et al., 1999) can be avoided by using these techniques. This can be vital for objects which are very sensitive to these problems such as silicon wafers, glass plates used in flat panel displays, sub-millimeter sized electronics, or coated sheet metal. The levitated object is held at a certain position from the levitation tool by actively controlling the levitation force. It compensates for gravitational, inertial, and disturbance forces, and the object appears to be suspended by an invisible spring. The advantages of levitation systems have led to the development of several non-contact manipulation systems.

While using non-contact handling techniques solves the problems related to the direct physical contact that exists in regular contact-based handling, it also introduces new difficulties as these systems behave differently from conventional contact-based handling techniques. Especially if the manipulation task has to be performed by a human operator, as is still often the case in R&D environments or highly specialized production companies, non-contact manipulation tasks can become very difficult to perform. The main reason for these problems is the fact that the stability of levitation systems against external disturbances is much lower than that of conventional handling tools such as grippers. Inertial forces and external forces can easily de-stabilize the levitation system if they exceed certain critical threshold values. In case of human operation, the motion induced by the human operator is in fact the largest source of disturbances. Especially in the tasks of picking up and placing, where the status of *non-levitated* changes to *levitated* and vice versa, large position errors can be induced by the downward motion. The air gap between the tool and the object can not be maintained as in

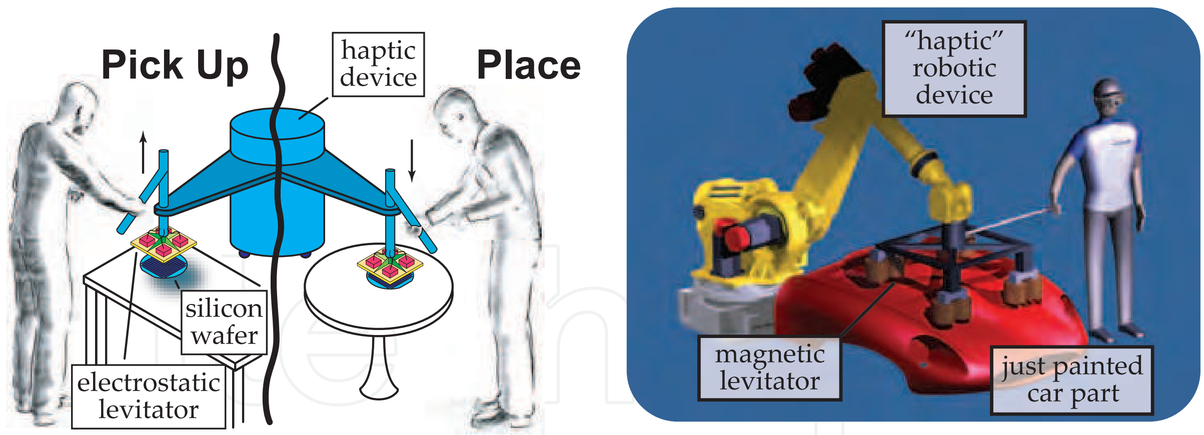


Fig. 1. A visual representation of the "Haptic Tweezer" concept. The human operator handles the non-contact levitator through the haptic device in order to augment in real-time the handling performance.

these tasks, the object is supported on one side by for example a table, while the levitator is moving down. If the motion is not stopped on time, contact between the levitator and object will occur, something which should be avoided at all cost in non-contact handling systems. In regular contact-based handling, the direct physical contact with the object directly transmits the reaction forces from the support which will stop the downward motion. The contact force also gives a tactile feedback signal on the grasping status *and* on whether or not the object is in mid-air or at a support. In levitation systems however, this direct contact force is missing and instead, the operator feels the reaction force of the levitation system which is far weaker and thus more difficult to sense. This means that the operator can easily continue his downward motion even though the object has already reached the correct position. This problem is even more eminent if the nominal levitation air gap between levitator and object is very small which is often the case in levitation systems. However, for the development of a practical non-contact handling tool, these challenges have to be overcome.

The main objective of this research is to develop a mechatronic non-contact handling tool that allows a human operator to perform simple manipulation tasks such as pick and place, in an easy and intuitive way. In order to realize that objective and overcome the challenges in terms of stability and robustness of such a human operated tool, a solution is sought in employing haptic technology to augment the human performance in real-time by active haptic feedback. This concept is named "Haptic Tweezer" and Fig. 1 shows some illustrations of the concept. The global idea is that haptic feedback compensates the disturbances coming from the human operator during manipulation tasks such as pick and place. By counteracting disturbances that would otherwise lead to instability (failure) of the levitation system, the haptic feedback will improve the performance of non-contact object manipulation. As the haptic feedback also restores in a sense the "feeling" of the levitated object, which was lost by the absence of physical contact, the task can be performed in an intuitive way.

The approach that is used for research on the "Haptic Tweezer" concept, has a strong experimental character. Several prototypes have been developed to investigate different aspects of the "Haptic Tweezer" concept. Two different levitation techniques have been used, magnetic levitation and electrostatic levitation, and control strategies based on both impedance control and admittance control were used in order to realize satisfactory results. The results have

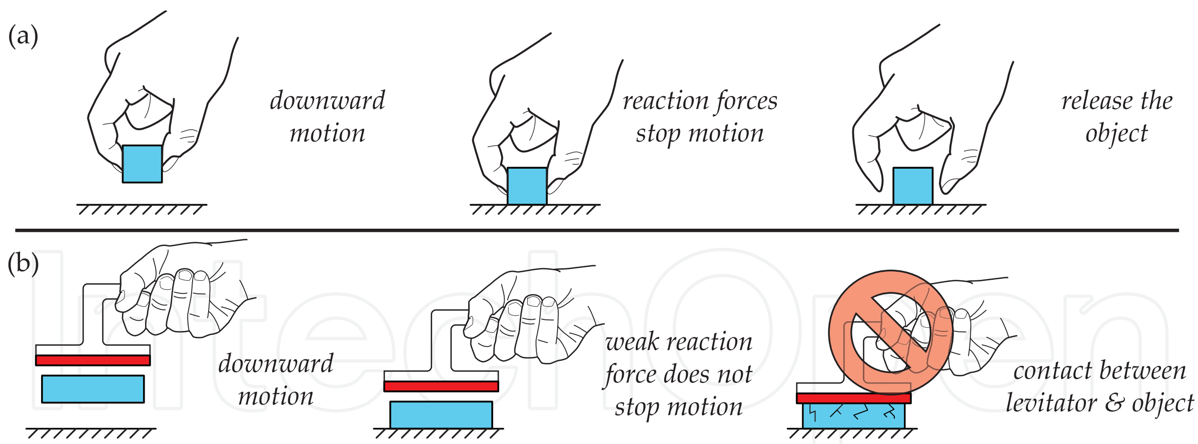


Fig. 2. Performing a placing task with (a) using direct physical contact, (b) using a non-contact levitation tool

shown that the haptic feedback has a significant beneficial contribution for handling objects without contact.

The general concept of the “Haptic Tweezer” concept will be further explained in the following section. A brief discussion on related research that uses haptic technology for real-time assisting applications is given in Section 3 and Section 4 will provide some basic background information on magnetic and electrostatic levitation systems. A first prototype that uses magnetic levitation and the impedance controlled haptic device PHANTOM Omni, is described in Section 5. Another prototype is described in Section 6, which uses electrostatic levitation and an in-house developed haptic device based on the admittance control strategy. The conclusions, describing the significance of the “Haptic Tweezer” concept, are given in the final section.

2. The “Haptic Tweezer” Concept

2.1 Basic concept

The concept of “Haptic Tweezer” uses the haptic device in a different configuration from most haptic applications. Typically, haptic devices are used in virtual reality applications or tele-operation systems to transmit tactile information, such that the operator can interact in a natural manner with the designated system. However, the output capabilities of the haptic device can also be used to modify, in real-time, the operators motion or force for other purposes. The human operator and the haptic device can perform a task collaboratively in which the haptic device can exert corrective actions to improve the performance of the task. This is precisely the objective of the “Haptic Tweezer” concept as the haptic device improves the task of non-contact handling by using haptic feedback to reduce the human disturbances to the levitated object.

The levitation systems used for non-contact handling have an independent stabilizing controller based on a position feedback loop. This same position information can be used as a measure of stability of the levitation system, i.e. large disturbances will induce large position errors in the levitation system. The largest levitation errors that are induced by the human operator will occur during the tasks of *picking up* and *placing*. This problem is graphically shown by Fig. 2, where a placing task is performed by using direct physical contact (a), as well as by using a non-contact levitation tool (b). In regular contact-based handling, the motion is

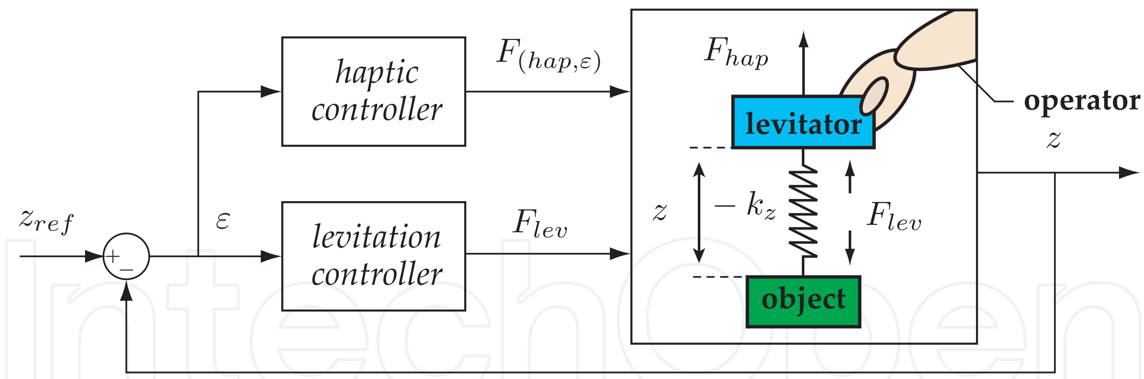


Fig. 3. Realization of an additional haptic force feedback loop

stopped by the reaction forces coming from the table, supporting the object. It also signals the operator that the correct location has been reached. In case of non-contact handling however, the downward motion is not stopped by the reaction forces from the levitation system as they are very weak. Furthermore, the human operator does not stop his motion as he can hardly "feel" the exact moment the object reaches the correct location. The induced position disturbance is too large for the levitation system and the air gap between levitator and object can not be maintained. The main focus of the "Haptic Tweezer" concept will lie in performance improvements for these pick and place tasks.

To compensate for the human disturbances, the haptic device will use the levitation position error to generate the haptic feedback to the operator. For example, if the human operator's downward motion reduces the air gap between the object and the levitation tool, the haptic device will generate a force to prevent this motion and thus avoid instability and damage. This is also shown in Fig. 3, where the haptic controller generates a feedback force $F_{hap,\varepsilon}$ based on the levitation position error ε. It is important to note that the haptic loop is an *addition* to the levitation controller that controls the force F_{lev} that stabilizes the leviation system. With the combination of the haptic controller *and* the levitation controller, a large induced position error will result in a reaction force from the levitation system (weak and hardly noticeable) and a force from the haptic device (strong) that counteract the position error. Furthermore, the haptic force sensation will naturally make the operator stop his downward motion as he can "feel" the status of the task he is performing. The haptic device allows the human operator to perform these pick and place tasks in a natural way and with improved performance as instabilities can be prevented.

2.2 Other contributing haptic effects

There are several other haptic effects that can further contribute to the "Haptic Tweezer" concept and a basic list of haptic effects comprising the "Haptic Tweezer" concept are described below and some are shown graphically in Fig. 4:

- Haptic feedback based on levitation position error (main)
- Damping force to restrict high accelerations
- Suppression of human hand vibration
- Virtual fixtures for guiding
- Gravity compensation of levitator and object

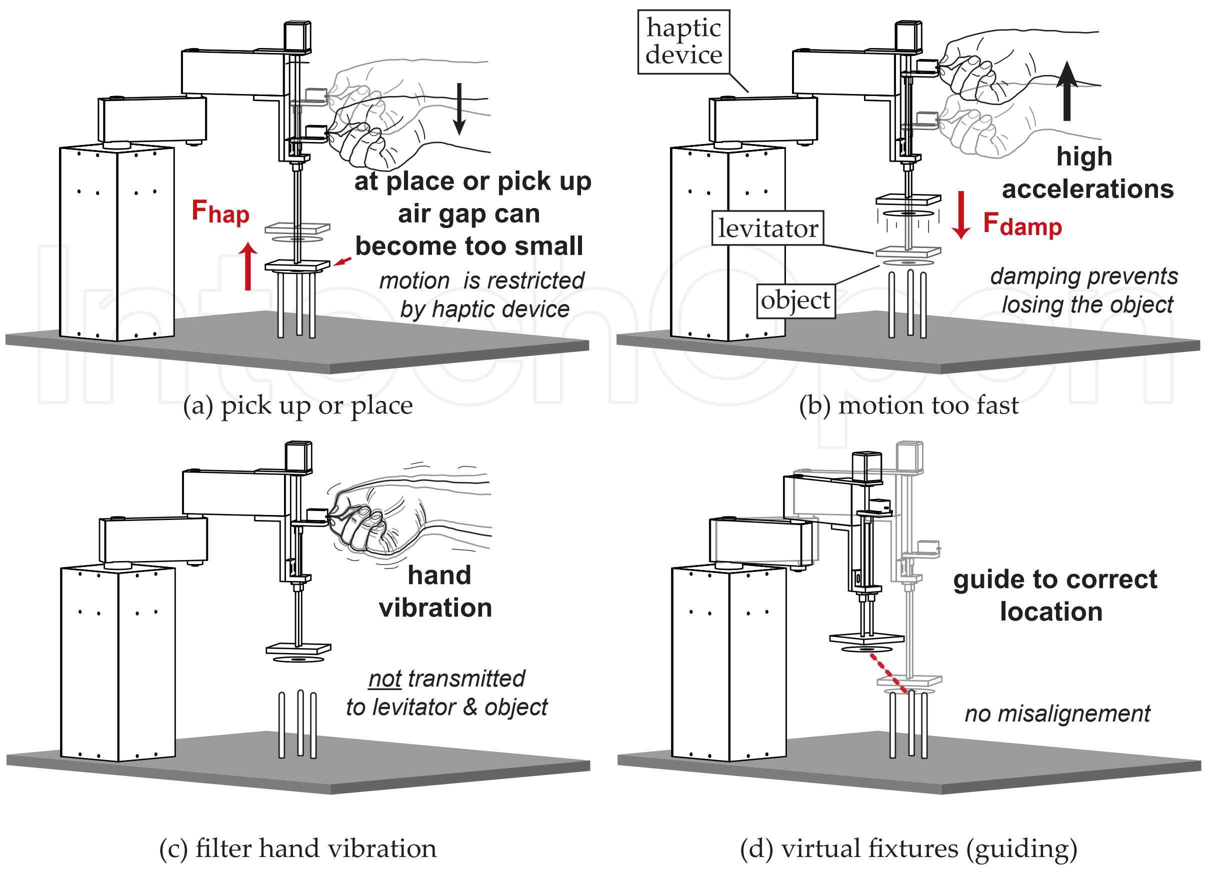


Fig. 4. Several haptic effects that can contribute to the “Haptic Tweezer” concept

The effect of creating a virtual damping field will damp sudden accelerations that could be the result of wild motion and it will smoothen the resultant motion as shown in Fig. 4(b). The performance of precision handling can be further enhanced by filtering and suppressing the human natural hand vibrations as shown in Fig. 4(c). It can be realized through the mechanical structure of the haptic device and by filtering the operator’s input. This idea is not unique to the “Haptic Tweezer” concept as other researchers have realized devices with the same objective and strategy, namely the Steady Hand Robot (Taylor et al., 1999). Virtual fixtures, shown in Fig. 4(d), can be used to guide the operator’s motion and this technique is commonly used in various haptic applications. Lastly, the haptic device can assist in carrying the levitation system and object to reduce the task load of the operator. This list might be further extended with more effects at a later stage. However, the work presented in this chapter will mainly focus on the improvements that can be realized by the haptic feedback based on the levitation position error.

2.3 Various configurations & possible applications

The concept of “Haptic Tweezer” can be applied to various applications. In this section some configurations are described to give insight in where the “Haptic Tweezer” can be used. An overview is given in Table 1. However, this is just a selection of possible applications. The concept of “Haptic Tweezer” is general and can be applied to any situation which requires non-contact object handling and is therefore also not limited to only magnetic and electrostatic levitation systems.

In the first configuration, the "Haptic Tweezer" can be applied to handle very flat and thin fragile objects such as silicon wafers or the glass plates of Flat Panel Displays (FPD). Because of their large surface area, they can be levitated by electrostatic levitation which has the benefit that the levitation force is divided over the whole area and prevents bending (internal stress) of the flat objects.

The second configurations deals with precisely machined products which have to be moved without being contaminated. The tasks of picking up the object and placing it have to be performed with high accuracy which could be realized through the "Haptic Tweezer" concept.

In the third configuration, the "Haptic Tweezer" concept can be applied to handle objects in the (sub)-millimeter order. An example could be placing solder beads, which have to be aligned accurately for soldering of electronic chips. Or the assembly of minute parts, such as mechanical components like small gears and pins or assembly of electronic components on a printed circuit board.

In the last configuration, a piece of sheet metal that has been processed with a special coating (like paint) has to be transported without any contamination. This can be realized by magnetic levitation.

Application	Reason for non-contact handling	Levitation technique
1. Wafer / FPD glass plate handling	fragile	electrostatic
2. Precision placing	contamination	magnetic
3. Micro object handling	stiction	electrostatic / magnetic
4. Processed sheet metal	contamination	magnetic

Table 1. Several possible configurations / applications of "Haptic Tweezer"

3. Related research

The usage of haptic technology for real-time assisting applications, is a relatively new field within the haptic community that has an overlap with the field of Human-Machine Collaborative Systems (HMCS). The advantages of such a collaborative system are that the high precision and large endurance of robotic devices are combined with the intelligence and flexibility of a human operator. A system, in which a human operator and a robotic / haptic device work closely together, can realize results that would be not possible by only a robot or only a human operator. One field within the haptic community in which this development has taken place is the area of Computer Aided Surgery. The Steady Hand robots (Taylor et al., 1999), developed at the Johns Hopkins University (JHU), are a good example of such a class of assisting robotic tools. The key idea is that the tool the surgeon is holding, is kinematically connected to a mechanical device that provides high stiffness, high accuracy, and haptic feedback to the operator. The result is a smooth, tremor-free, precise positional control with capability of force scaling.

In the field of HMCS, the early collaborative robots, or *cobots* (Peshkin et al., 2001) are rather passive devices to support the human operator in terms of power (Hayashibara et al., 1997; Lee et al., 2000) that allows humans to perform heavier tasks for longer periods of time. An interesting development in this field which has brought the interaction even closer, is the development of wearable exoskeletons aiming to increase the human performance, with impressive results (Kazerooni, 1996; Kazerooni & Steger, 2006). In these systems, a close interaction between human and device is required and using haptic signals can facilitate this interaction as it allows more natural and comfortable operation. The fast processing of haptic signals by humans makes that haptic technology plays a key role for realizing systems that are intuitive to operate. Haptic signals can be used to present key information to an operator in for example augmented reality systems (Azuma et al., 2001; Azuma, 1997) to make the operator accept all the presented information more easily.

The possibilities are even larger as haptic devices can even transform sensory information, such as optical information, by presenting it haptically through the sense of touch. The SmartTool (Nojima et al., 2002) is a good example of such a system as it converts or “haptizes” information in real-time from an additional sensor into a haptic feedback. One example from their work shows the potential of such a system. The end-effector of the haptic device consists of the tool with an additional sensor, in this case, a surgical scalpel fitted with a reflectivity sensor. The objective will be to remove some unwanted tissue, for example a cancer growth, from a healthy organ, without damaging the healthy organ. For the experiment, the human tissue is replaced by a hard-boiled egg. A threshold in reflectivity is defined as a boundary between tissue that is safe to cut (egg white) and vital tissue (the egg yolk) that should be unharmed during a surgical cutting procedure. When the reflectivity sensor senses the egg yolk, a repulsive force is generated to compensate the operators cutting force. In such a way, the egg can be dissected without any effort from the operator. The strength lies in the ease with which such an operation can be performed and it shows the great potential of employing haptic technology. In addition, the usage of virtual fixtures (Rosenberg, 1993) can further enhance performance of some tasks as the operator’s motion can be confined or guided, which increases performance of manipulation in for example medical tasks (Bettini et al., 2004; Lin et al., 2006).

4. Magnetic and Electrostatic Levitation

This section provides a brief introduction to the magnetic and electrostatic levitation systems used in this research. Both techniques have been researched by other researchers, so many literature is available on these subjects and this section is largely based on some of these works (Jin et al., 1994; 1995; Schweitzer et al., 1994).

4.1 Theoretical equations of motion

Magnetic and electrostatic levitation systems have similar characteristics as the generated attractive force is strong when the object is near the levitator, but gets quadratically weaker when the air gap increases. Therefore, according to Earnshaw’s theorem (Earnshaw, 1842), active control is necessary for stable levitation. For a magnetic levitation system, as shown in Fig. 5 on the left side, the attractive electromagnetic force $\tilde{F}_{EM}$ is generated in a magnetic circuit that has a coil current $\tilde{i}$ and a permanent magnet. The force is given by

$$\tilde{F}_{EM} = \frac{A\mu_0 \left(\frac{B_r l_m}{\mu_0} + N\tilde{i} \right)^2}{(l_m + 2\tilde{z})^2}, \tag{1}$$

where A is the area of the magnetic flux path, μ_0 is the permeability constant, B_r is the remanent flux density of the permanent magnet, l_m is the length of the permanent magnet and N is the number of coil windings. For simplicity, the magnetic levitation is assumed to be quasi-static, and effects such as saturation, heat loss and leakage flux are ignored. Even though

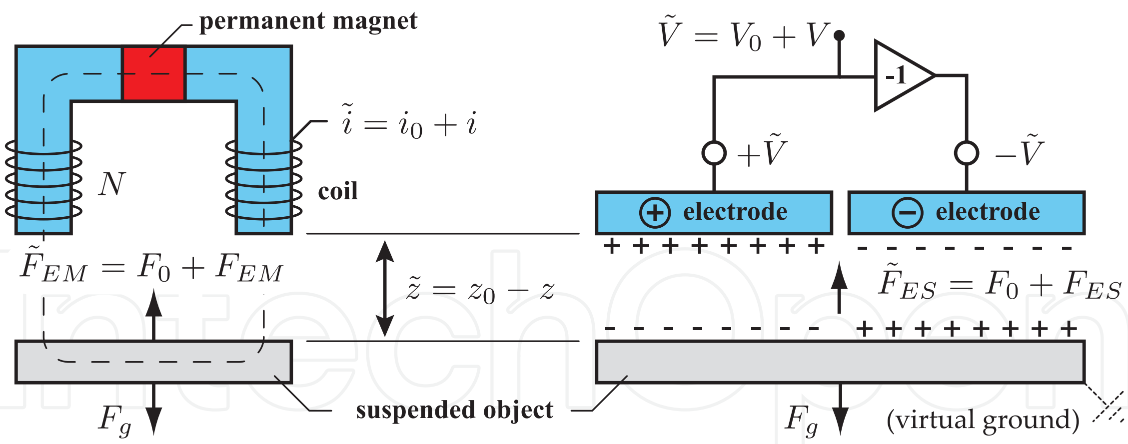


Fig. 5. Magnetic levitation system (left) and electrostatic levitation system (right). In magnetic levitation, the levitation force $\tilde{F}_{EM}$ is provided by a combination of a permanent magnet and an input current $\tilde{i}$. For electrostatic levitation, the levitation force $\tilde{F}_{ES}$ is generated by a high input voltage V applied to a pair of electrodes.

magnetic levitation can be realized without a permanent magnet, the permanent magnet reduces the required coil current since it provides a bias attractive force.

The electrostatic levitation system is shown in Fig. 5 on the right side; the attractive electrostatic force $\tilde{F}_{ES}$ is the result of an electric field that is generated by applying a high voltage $\tilde{V}$ to a pair of electrodes. The force is given by

$$\tilde{F}_{ES} = \frac{\varepsilon_0 A \tilde{V}^2}{2\tilde{z}^2}, \tag{2}$$

where A is the active area and ε_0 is the permittivity of air. By using a pair of positive and negative electrodes, the potential of the object can remain zero (virtual ground). For levitators controlling multiple n DOF, some of the electrodes can be combined, with a minimum of $n+1$ electrodes to control all DOF and maintain a zero potential of the object.

These levitation forces can be written in a more general form that holds for levitation systems where the levitation force $\tilde{F}(\tilde{u}, \tilde{z})$ is generated through input $\tilde{u}$ and also depends on the air gap $\tilde{z}$. Typically, the force equation is linearized around the operating point (u_e,z_e, and F_e) where the attractive force equals the gravitational force ($F_e = mg$). With deviations from the operating point as defined in the figure, the linearized force equation is

$$m\ddot{z} = k_u u + k_z z, \tag{3}$$

where m is the mass of the levitated object, k_u is the force-input factor, k_z is the force-displacement factor and

$$k_u = \frac{\delta \tilde{F}}{\delta u}(u_e, z_e), \quad k_z = \frac{\delta \tilde{F}}{\delta z}(u_e, z_e), \quad F_e = \tilde{F}(u_e, z_e). \tag{4}$$

The transfer function of this levitation system H_{SYS}, is derived from (3) in the Laplace conjugate domain, where each variable is capitalized and initial conditions are assumed to be zero:

$$H_{SYS} = \frac{Z(s)}{I(s)} = \frac{k_u}{ms^2 - k_z}. \tag{5}$$

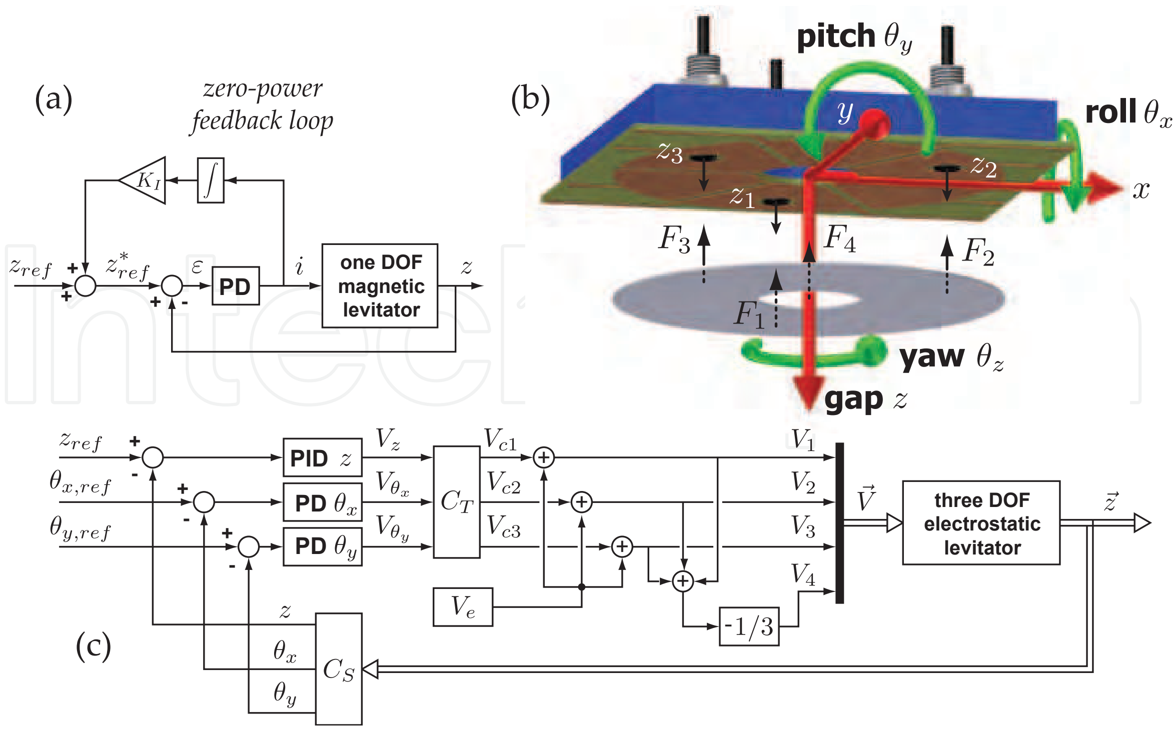


Fig. 6. (a) Zero-Power controller for magnetic levitation system. (b) Coordinate system for disk-shaped object used in electrostatic levitation. (c) Centralized controller for electrostatic levitation of a disk-shaped object.

It shows that the system behaves as an unstable mass-spring system because the spring stiffness is negative ($-k_z$). The following section will describe the stabilizing controller and how it influences the pick and place behavior.

4.2 Stabilizing levitation controller for one DOF

For a one DOF levitation system as (5), a simple Proportional-Derivative (PD)-controller is sufficient to realize stable levitation. The proportional gain will transform the negative spring constant to a positive value with stiffness $k = K_P \times K_u - k_z$. The derivative gain K_D will provide the necessary phase lead (damping) to the system such that there is enough phase-margin.

In addition to the PD-controller, an integral loop can be added to the system for further enhancing the controller performance. Such a loop can be a feedforward loop as in regular PID-control, or in a feedback loop, which is often lesser known. When the integral gain is a feedforward loop, the controller converges the steady state output to the reference *input* value to minimize the position or tracking error. However if the integral gain is in a feedback loop, the *output* of the controller is minimized. Such a controller is shown in Fig. 6(a) and is sometimes used in magnetic levitation systems to minimize power consumption under the name of Zero-Power controller (Morishita & Azukizawa, 1988). Power consumption can be minimal if the levitated object is in a position where the levitation force is almost completely provided by the permanent magnet. Current is still required to stabilize the system, but it can be virtually zero at steady state. If for example an additional load is added to the levitated object, the controller will bring the object to a new position, disregarding the original reference position input z_{ref}, closer to the levitator as the force from the magnet is stronger when the object is closer. It can be perceived as that the integral loop modifies the reference input to z^*_{ref}, which resembles a position in which the gravitational load is always balanced by the bias force of the levitation system (e.g. permanent magnet in magnetic levitation). The main benefit of Zero-Power controlled levitation systems and the reason why it is so suitable for non-contact transportation systems, is that the weight of the object can vary while still maintaining low power consumption for the manipulation task.

The integral gain loop in the levitation controller has another effect that is used in the *placing* task. The presence of such an integral loop allows to release the levitated objects automatically without any manual switching. This phenomena, which is described extensively in (van West et al., 2008), uses the integral controller wind up to reduce the holding force when a position error is temporarily forced to the levitated object. When, for example, the levitated object is brought to the desired location in the placing task, making contact at that location will reduce the air gap between levitator and object (the position error). For both Zero-Power and PID control, the result of this position error is that the controller will aim to increase the air gap by reducing the attractive force. The key point is that the integral gain will keep reducing the attractive force even if the position error is constant, due to the integral action. After some time, the attractive force has been reduced so much, that when the levitator moves away again and the position error changes sign, the object can not re-levitate the object and the placing has been realized automatically. Manually disabling the levitation force, on the other hand, would require precise timing as a release too early can drop the object, and a release too late can force the object to "stick" to the levitator. Automatic release will relief the operator in this regard and it contributes to perform the manipulation task intuitively. In the experimental results of the *placing* task, a more detailed description will be given using the experimental data.

For the *picking up* task however, having an integral gain in the levitation controller can be undesired for the same reason: integral controller wind up. If for example the picking up motion is too slow, the controller will increase the attractive force so much, that when the position is reached from which levitation is possible, the attractive force can be so large that instead of going to a stable position, it will "jump" and stick to the levitator. So in order to use the beneficial effects of the integral gain loop only when it is needed, it can be automatically switched on just after initial levitation (picking up) by a relay switch.

4.3 Multiple DOF levitation systems

While some objects can be levitated by actively controlling only one DOF, as will be shown in the first prototype of magnetic levitation of an iron ball, for most objects, multiple DOF have to be controlled for realizing stable levitation. For this purpose, multiple actuators and gap sensors have to be placed strategically around the object. However, it is not always necessary to control all six DOF with active control, as often a passive restoring force is present that naturally stabilizes some of the DOF. For levitating thin circular objects like an aluminium disk for example, it is natural to control only three DOF, namely the gap z, the roll θ_x, and the pitch θ_y, shown in Fig. 6(b). The lateral x- and y-direction are stabilized by a passive force that aligns the object with the levitator because in this position, the levitation field potential is the highest (Woo et al., 1995). As the side area is too small to place additional actuators, this force cannot be enhanced by means of control. Lastly, control of the yaw rotation θ_z is unnecessary due to the rotation symmetry of the object. As the actuators are all acting on the top surface of the object, the levitator can have the same form factor as the levitated object, which is very useful in the manipulation tasks of picking up and placing, where actuators on the side or bottom could be obstructive.

The controller structure for levitating an aluminium disk by electrostatic levitation is shown in Fig. 6(c) and it has a centralized control structure as each DOF is controlled by its own controller (Jin et al., 1995). The relative position of the disk is measured by three gap sensors, which are radially distributed around the z-axis at a radius R_s. Since these gap sensors will measure the distance z_i, $(i = 1, 2, 3)$ in local coordinates, they have to be transformed by a transformation matrix C_S to the correct DOF:

$$\begin{bmatrix} z \\ \theta_x \\ \theta_y \end{bmatrix} = \underbrace{\begin{bmatrix} 1/3 & 1/3 & 1/3 \\ \frac{-2}{3R_s} & \frac{1}{3R_s} & \frac{1}{3R_s} \\ 0 & \frac{-1}{\sqrt{3}R_s} & \frac{1}{\sqrt{3}R_s} \end{bmatrix}}_{C_S} \times \begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix}, \tag{6}$$

which assumes that tilting angles are small ($\sin(\theta) \approx \theta$). As the actuators have the same radial distribution as the gap sensors, the output from the controllers have to be transformed once again to generate the input signal for each actuator:

$$C_T = \begin{bmatrix} -1/3 & \frac{2}{3R_a} & 0 \\ -1/3 & \frac{-1}{3R_a} & \frac{1}{\sqrt{3}R_a} \\ -1/3 & \frac{-1}{3R_a} & \frac{-1}{\sqrt{3}R_a} \end{bmatrix}, \tag{7}$$

where R_a is the radius at which the actuating force occurs. By using C_T as the output transformation matrix, the proportional controller values of K_P will have the correct physical value of stiffness realized by control once they are multiplied with the force-input value of K_u.

In this case of electrostatic levitation, the positive electrodes are the controlling electrodes as they receive the output voltages of the controller $V_i, \quad i = 1, 2, 3$. The negative electrodes receive a voltage that will simply maintain the total potential of the object at zero volt by setting $V_4 = -1/3 \sum V_i, \quad i = 1, 2, 3$.

5. Prototype using magnetic levitation, PHANTOM Omni, and impedance control

The first prototype is realized to show how a combination of levitation system and haptic interface will perform. This prototype combines a magnetic levitation system with a commercially available haptic interface, the PHANTOM Omni (Sensable Technologies). This section describes the control strategy, the realized prototype, and the experiments that were performed to evaluate the overall performance.

5.1 Strategy for impedance controlled haptic devices

For the first prototype, the haptic device PHANTOM Omni has been used as it is commercially available at relatively low cost, and it can be easily equipped with a simple one DOF magnetic levitation system. The PHANTOM Omni is a haptic device based on the impedance control strategy, measuring the operator's position input and feeding back the haptic force (position in / force out). The implementation of the "Haptic Tweezer" concept for such a device is graphically shown in Fig. 7. The upper part shows the impedance structure of the haptic device with the position sensor measuring the human motion p, and the force actuator exerts the haptic feedback force F_{hap} based on a reference force F^*. One component of this reference force signal, F_v, comes from a virtual model that defines the haptic environment, and it

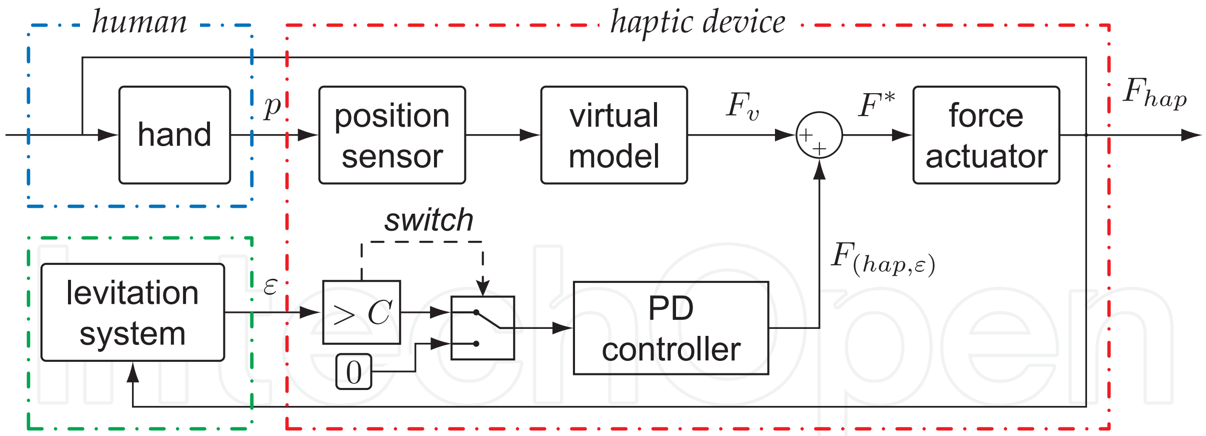


Fig. 7. Interaction between human, haptic device and the levitation based on the impedance control strategy

contains conventional parameters such as inertia and damping to realize comfortable motion. The additional haptic loop based on the levitation error ε is added to this virtual model such that a haptic force is generated as $F_{hap,\varepsilon}$ when the levitation error exceeds a certain threshold value C. The gain of this force can be regulated through a haptic PD-controller which acts like additional spring and damper elements for optimal results.

One drawback of using impedance controlled haptic devices, is that their performance in terms of output force and realizable stiffness is limited (van der Linde & Lammertse, 2003). This is a direct result of the design of these devices as they have to be lightweight and highly back-drivable to minimize their inertia and friction, which will always be felt by the operator. Such a limitation can be a problem if the levitation system is so sensitive that it requires larger force/stiffness values in order to compensate for the operators picking up or placing action. For the prototype discussed in this section, successful results could be obtained, but later on, another prototype will be described for which another type of haptic device had to be used.

5.2 Experimental setup

The magnetic levitation device consists of a hybrid electromechanical system and it is shown in Fig. 8, attached to the haptic device. The electromagnet has 530 windings in an E-core and a permanent magnet (type Nd-B-Fe, $B_r = 1.2$ T) is attached to the central leg. The air gap $\tilde{z}$ between the electromagnet and the object is sensed by an optical parallel beam linear sensor (Z4LB-S10V2, Omron). The absolute maximum coil current is limited at 1.2 A to prevent overheating of the coil. With this setup, only one DOF is actively controlled as the other two DOF are passively stable. The levitation controller is a Zero-Power controller as shown in Fig. 6(a) with the controller gains given in Table 2. Other parameters of the leviation setup are given in this table as well. Note that as mentioned earlier, a relay switch is implemented that automatically switches the integral feedback loop *off* for the *picking up* task.

The haptic controller, has a proportional gain K'_P on the air gap error and a gain K'_D on the differentiated air gap with values as shown in Table 2. Summed, a vertical upward force (z-direction) is generated at the stylus when an air gap is forced smaller, e.g. the object is placed on a surface. An extra stiffness is experienced by the operator, limiting the reduction of air gap. However, generating a haptic feedback force when there is a position error due to a larger air gap can give an undesirable effect. During the *picking up* task for instance, there

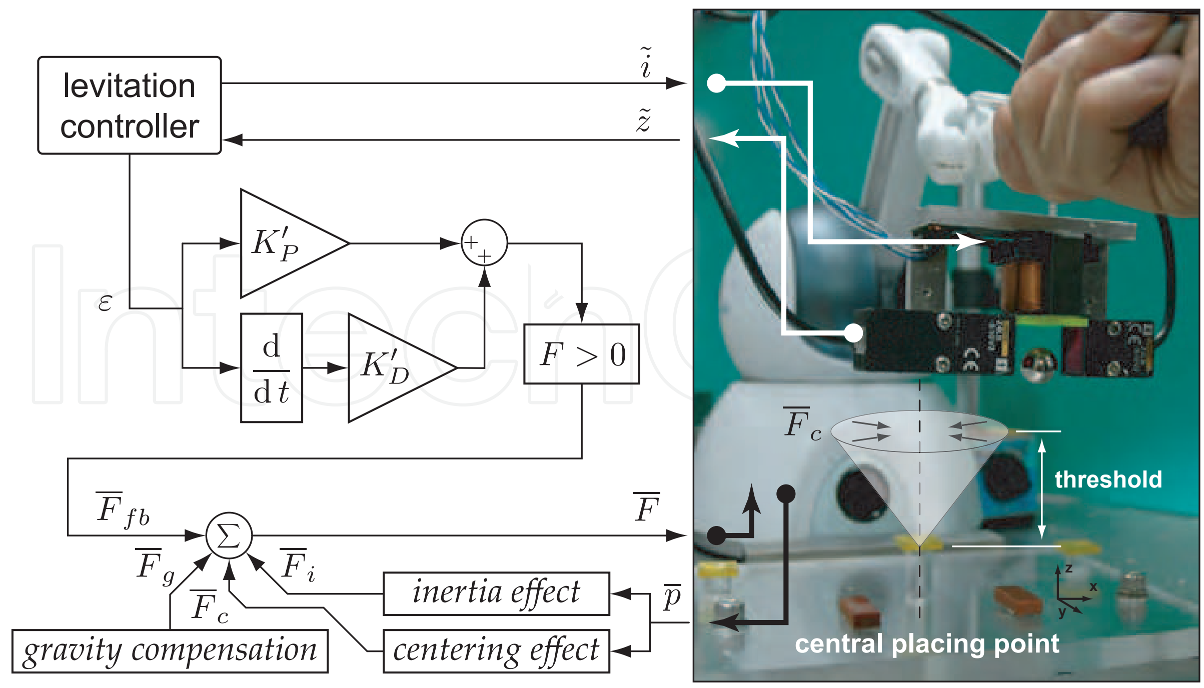


Fig. 8. Control structure for the prototype that uses magnetic levitation and the PHANTOM Omni to pick and place an iron ball, 12.7 mm in diameter

is a position error because the air gap between levitator and object is large. In this case, the haptic force would try to reduce the position error by moving the levitation device down to the object. As a result, the operator's motion is disturbed and he can no longer exert a controlled motion for the *picking up* task. Therefore, the haptic force can be limited to one direction only, namely the vertical upward direction and only when the position error is due to a smaller air gap. This is shown in Fig. 8 by the "$F > 0$"-block. The feedback force $\overline{F}_{fb}$ is further combined with a gravity compensating force $\overline{F}_g$ of 1.5 N to assist the user in carrying part of the weight of the levitation device (about 255 g) and artificial inertia ($\overline{F}_I$) is simulated to prevent sudden or rapid movements. The centering effect ($\overline{F}_c$) is used as a virtual fixture in the comparison experiment to guide the user to the correct pick and place location. It is further described in the comparison experiment, but also shown in Fig. 8. The total stiffness that is realized by the combination of magnetic levitation and haptic device is 452 N/m, which is roughly five times larger than the original stiffness realized by only the levitation controller. This is limited by the maximum force output of the haptic device and in fact a higher value of this stiffness is desired for this setup. As stronger haptic devices than the PHANTOM Omni are available, there is a potential to increase the performance here.

Another limitation of this prototype is the fact that the levitation device should be maintained level. This is necessary to keep stable levitation, but there is no mechanism present to achieve this. Thus, in this current setup, the operator has to maintain the horizontal position of the levitation device. It deviates from the concept that the tool should be natural and instinctive to use. Future prototypes should be designed to avoid this limitation.

5.3 Experimental results

To evaluate the additional performance of the haptic device to the levitation setup, three experiments based on a simple *pick and place* task were carried out. First, the details of the *picking up* task are presented followed by the details of the *placing* task. These tasks are then performed by a group of ten test subjects to evaluate the difference between the haptic effect *ON* and *OFF*. For this purpose, the iron ball has to be picked up and placed on a raised platform that has an absolute height of 63 mm.

Levitation		
Proportional gain	K_P	$2 \cdot 10^3$ A/m
Derivative gain	K_D	27.5 (A· s)/m
Integral gain	K_I	$1.2 \cdot 10^{-3}$ m/(A· s)
Force-current relation	k_u	$6.2 \cdot 10^{-2}$ N/A
Force-air gap relation	k_z	-32 N/m
MagLev stiffness	k_{MagLev}	92 N/m
Haptic Force		
Haptic proportional gain	K'_P	360 N/m
Haptic derivative gain	K'_D	210 (N· s)/m
Total Stiffness	k	452 N/m

Table 2. Control settings and other characteristics of PHANTOM-MagLev prototype

5.3.1 Picking up

Details of the *picking up* task are shown in Fig. 9. The moment the ball comes into the sensing range of the magnetic levitation, the control output is activated and the levitation system tries to get the ball to the reference air gap. When the air gap is reached from which levitation is possible, the ball will "jump" to the reference position with some overshoot after which it settles at the steady state position where controller current is zero. This overshoot and jump speed result in a repulsive force from the haptic interface at the stylus and the operator can feel that the ball is picked up through this force sensation. In this way, the object is picked up in a natural way by bringing the tool close to the object and because of the force sensation, the operator can feel the *picking up* is successful.

5.3.2 Placing

For the *placing* task, it is important to note that two effects will realize natural placing behavior. First of all the haptic interface will restrict the placing motion in such a way that the position error will remain within stable limits. Second, ZP-control allows for a natural release of the object due to the levitation controller wind up. Details of the *placing* task are shown in Fig. 10. The tool and object are moved down until the object makes contact with the surface (I). A forced reduction in the air gap leads to an upward force on the stylus (II) from the haptic device, which is experienced as an extra stiffness between the stylus and the object. Due to the behavior of the ZP-controller, the reduced air gap will increase the reference gap z^*_{ref} exponentially and the levitation system will try to bring the object to this larger air gap. The downward electromechanical force will increase (III) and so will the haptic upward force (IV). Due to the contact, the larger air gap cannot be realized until the operator retreats the tool from the object (V) and the air gap increases. As it takes time for z^*_{ref} to reduce, the reference gap is too large (levitation force is to weak) to re-levitate the ball (VI). The result is that the object will remain on the placing platform and placing is successful. In this way, both the ZP-controller and the haptic device contribute to a natural way of placing as the force sensation prevents

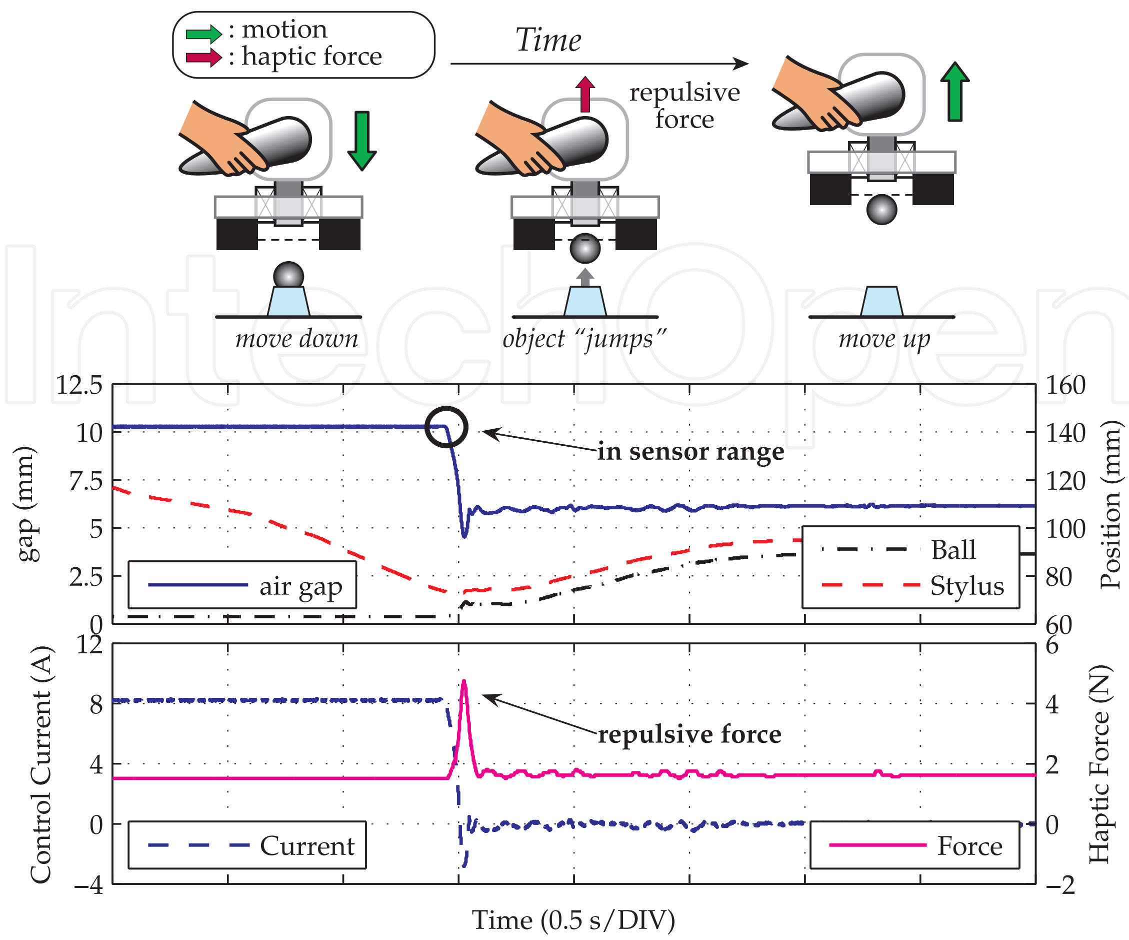


Fig. 9. Details of *picking up* with haptic assistance

instability and indicates when placing has been achieved. The placing sensation is natural and simple as there are no command or switch operations necessary to place the object. When the object makes contact at the desired location, further motion is prevented and the object will be automatically released.

5.3.3 Comparison experiment: approach

To evaluate the main effect of the haptic stiffness ($\overline{F}_{fb}$ in Fig. 8) on task performance, ten subjects (all male engineering students, age < 30 yr) with no experience on this device, performed a pick and place task. The only varying condition was the haptic stiffness either *ON* or *OFF*. As performance variables, the time for each task of *picking up* and *placing* is measured and failures are counted. Each subject had to perform 20 successful tasks while the number of attempts was not limited, but failures were recorded for later evaluation. Failures are classified as either "Stick", when the ball sticks to the levitation device, "Fell off", if the object was released but not on the desired location or as "Not Picked Up"/" Not Placed", when the attempt was made, but not successful without obvious failure.

The task duration is automatically measured as the difference in time when the operator moves the device passed a certain vertical height threshold, which is shown in Fig. 8. At this threshold, also the centering effect becomes active and a spring-like force related to the distance (in the horizontal XY-plane) to the central placing point will guide the operator to

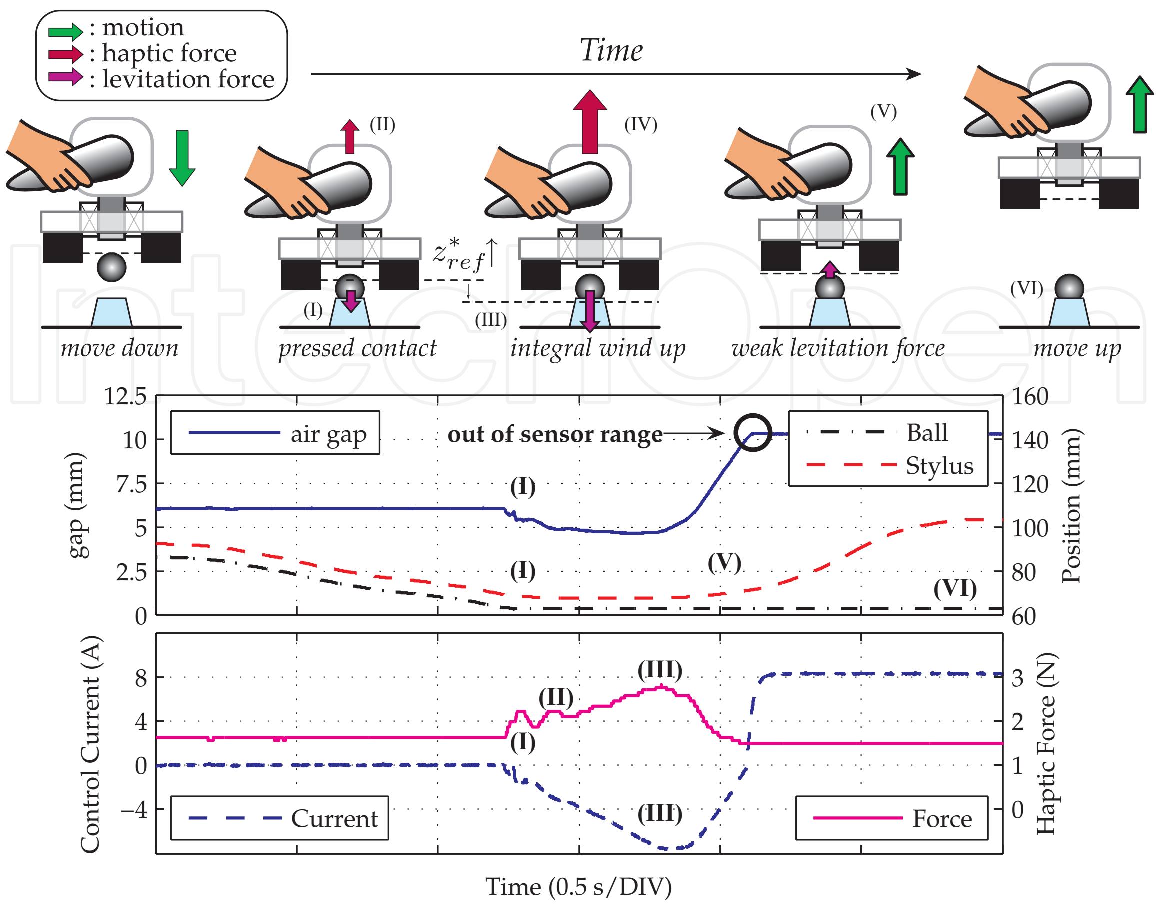


Fig. 10. Details of *placing* with haptic assistance

the right position. The spring stiffness of the centering effect is increased proportional to the vertical absolute position, giving a cone-shape vector field for constant centering forces.

Five subjects performed the task first with haptic stiffness *OFF*, followed by haptic stiffness *ON* (Group *OFF*→*ON*), but for the other half of the test subjects, the order was reversed (Group *ON*→*OFF*). All subjects were asked to perform the task in a natural way and they did not have any practicing time to get familiar with the setup, so they are considered as novice users. They also performed the same experiment at least a day later, with the only difference that they were given a 3 minute practicing time before each task, to enhance their skill and they are considered as experienced users. All experienced users performed the task in reversed order as when they were novice users.

With this approach, the performance can be evaluated under the effect of haptic stiffness. The average time of 20 *successful tasks* will give an indication on the handling speed, whereas the number of failures in the first 20 *attempts* can give insight on the frequency of failures. Also, the practicing effect can be analyzed by comparing the experienced group with the novice group. Any individual learning effect that might occur for the novice group within the 20 *successful tasks* is neglected as it can be considered equally distributed between the two groups.

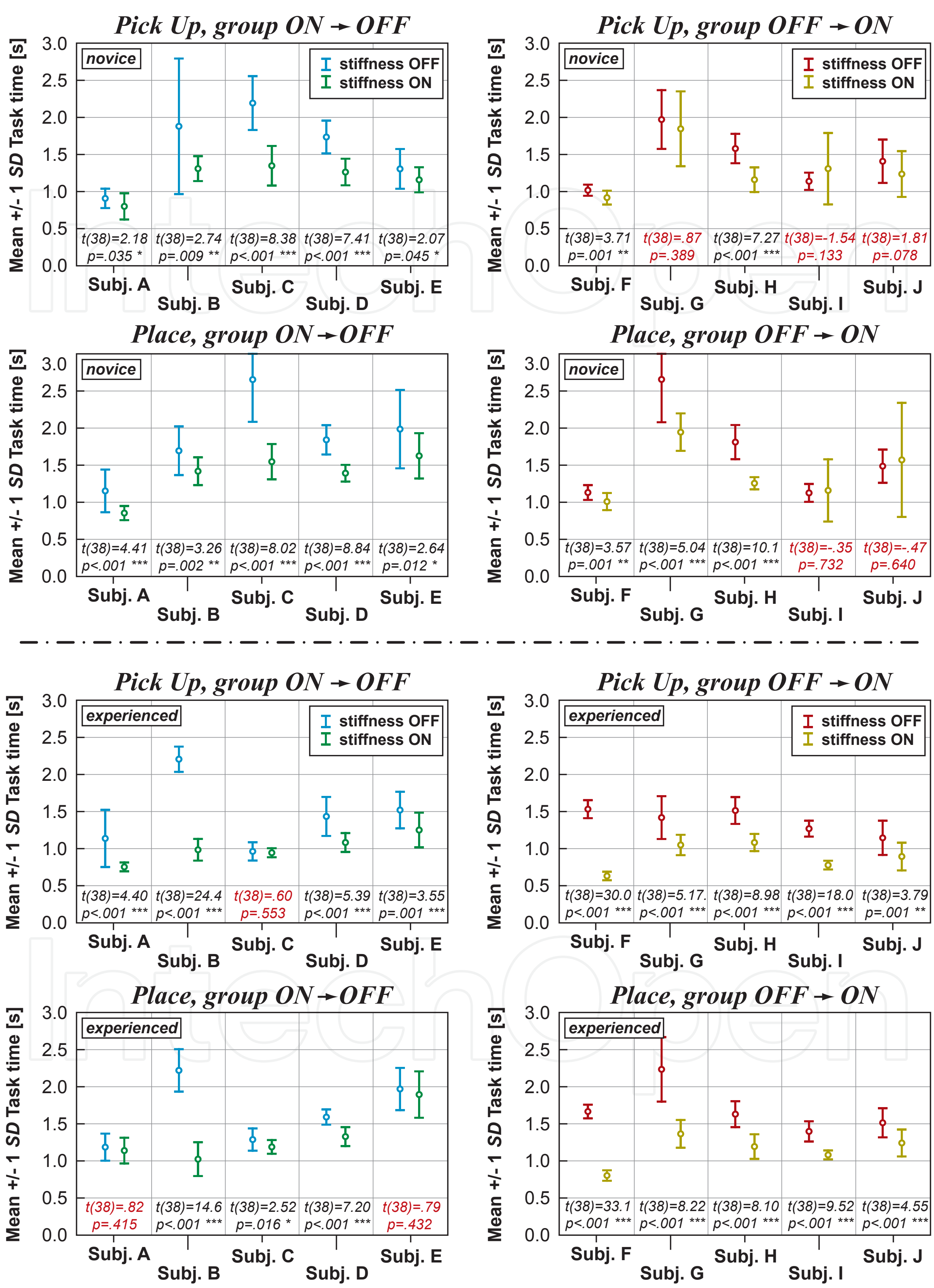


Fig. 11. Evaluation of *picking up* and *placing* by both novice operators (top four) and experienced operators (bottom four).

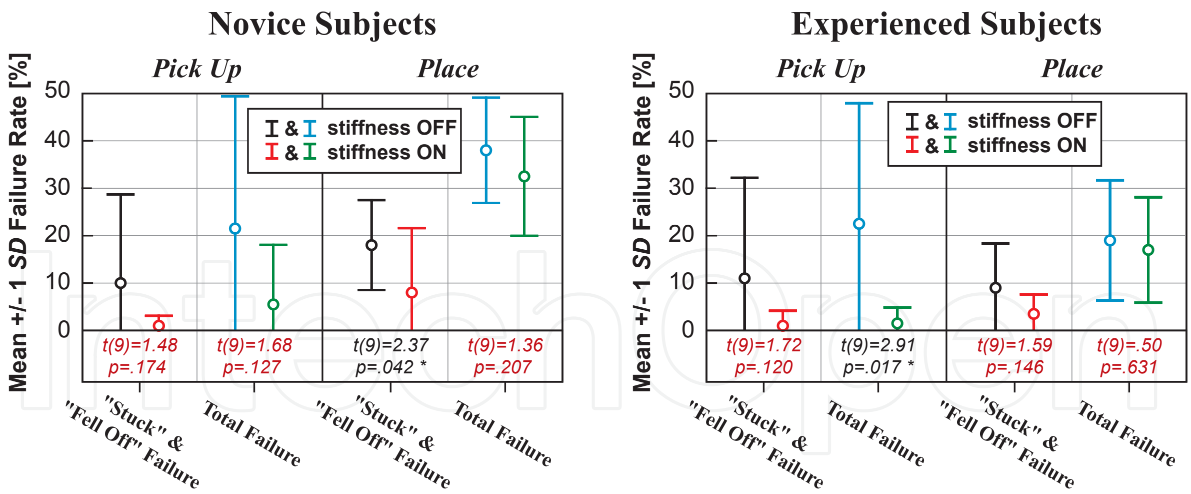


Fig. 12. Evaluation of the failure rates for both *picking up* and *placing*.

5.3.4 Comparison experiment: results

The average task time of 20 successful tasks is compared by an independent-samples T-test to verify if the task time is improved and the results are given in Fig. 11 for novice users (top four graphs) and for experienced users (bottom for graphs). A comparison of the failure rate of the first 20 *attempts* by a paired-samples T-test is provided in Fig. 12. Results, shown with an asterisk (*) have a p-value lower than the significance level $\alpha = 0.05$. Double asterisks (**) and triple asterisks (***) indicate significance levels of $\alpha = 0.01$ and $\alpha = 0.001$ respectively.

For novice users which performed the experiment in the order *OFF*→*ON*, the task time of both *picking up* and *placing* is significantly reduced with haptic stiffness *ON*, which could also be partly the result of a learning effect. For the novice users who performed the task in order *ON*→*OFF*, some improvements are not significant or even show deteriorated performance (e.g. Subj. I). Still the overall improvement is enough to support the positive effect of haptic stiffness. Moreover, the influence of the learning effect is further reduced by the practicing time given to each subject when they do the experiment again as an experienced user. The effect of haptic stiffness is more clear as all subjects performed significantly better in both tasks with few insignificant exceptions. The practicing effect improves the task time especially when the haptic stiffness is *ON* as can be seen in Table 3, where the average task times of all subjects are compared between the novice and experienced user by a paired-sampled T-test.

For the Failure analysis, a difference is made in strong failures such as “Stick” and “Fell Off”, and weak failures as “Not Picked Up”/“Not Placed”. In Fig. 12 both the weak failures and all failures (total) are shown for each case. Comparing the failure rates shows that in all cases there is a decrease of failure rate, which is however only significant in two cases.

At the *picking up* task, the failure rate is most clearly reduced for the experienced subjects as it is lower than 2%. It was observed that for some subjects the number of weak failures in the *placing* task did not reduce, but sometimes even increased. Due to the haptic stiffness, the operator can feel the contact as opposed to without the stiffness. This sensation caused in some cases the operator to move up more quickly than when the haptic stiffness was *OFF*. As a result, the contact time was not long enough to realize placing and the number of “Not placed”-failures increased.

Overall can be concluded that the effect of haptic stiffness has a positive contribution in the performance of non-contact object handling. However, the haptic stiffness was set the same

Condition	*M*	*SD*	*t(9)*	*p*
picking up, OFF, Novice	1.51	.43	.60	.566
picking up, OFF, Experienced	1.42	.34		
picking up, ON, Novice	1.24	.28	3.57	.006 **
picking up, ON, Experienced	.95	.19		
placing, OFF, Novice	1.75	.57	.49	.639
placing, OFF, Experienced	1.67	.36		
placing, ON, Novice	1.38	.32	1.71	.121
placing, ON, Experienced	1.23	.28		

Table 3. Practising effect by comparing Novice with Experienced

for all subjects, based on a general assumed placing motion. The experiments showed that an individual setting of the haptic stiffness is desired for this prototype as the placing motion varies per person and better individual results can be achieved. However, this is undesired for the final tool and improvements on the robustness for one optimum setting should be realized. In future work, the possibility to add other elements (e.g. a damper) to the spring or change its specific behavior to achieve this, should be studied.

With the reduction of task time and failures it is shown that it is more easy and instinctive to perform a pick and place task with haptic stiffness. Furthermore, with only a short time of practice, the performance increased and this indicates that the system has a degree of easiness to master.

6. Prototype using electrostatic levitation, SCARA-type haptic device, and admittance control

Another prototype has been developed for manipulating disk-shaped objects using electrostatic levitation. The haptic device used in this prototype is developed specific for this purpose but is still under development. This section describes the experimental setup and the results of the *picking up* and *placing* task.

6.1 Strategy for admittance controlled haptic devices

The limitations of impedance controlled haptic devices in terms of power and stiffness can give problems when the impedance controlled strategy of the "Haptic Tweezer" concept is applied to levitation systems which are very sensitive to disturbances, such as electrostatic levitation systems. For these systems, the levitation force is very weak and stable levitation is only possible at a very small air gap. Fig. 13 shows the difference in air gap between the magnetic levitation system used in the first prototype, and the electrostatic levitation system that will be described in this section. In order to apply the "Haptic Tweezer" concept also successfully to the electrostatic levitation systems, the requirements for the haptic device are higher. As the human operator's motion and force remain the same, the haptic device needs to be able to render a much higher stiffness for levitation systems with a small air gap.

By using an admittance controlled haptic device, these limitations can be overcome as an admittance controlled haptic device has the characteristics of being capable of rendering high

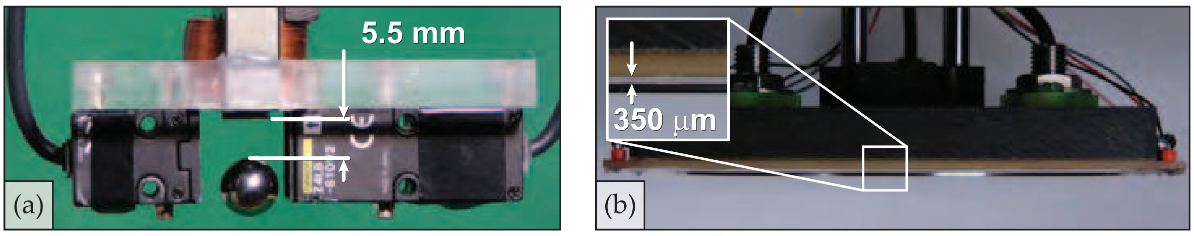


Fig. 13. Levitation system with different nominal air gap: (a) magnetic levitation of iron ball, (b) electrostatic levitation of aluminium disk

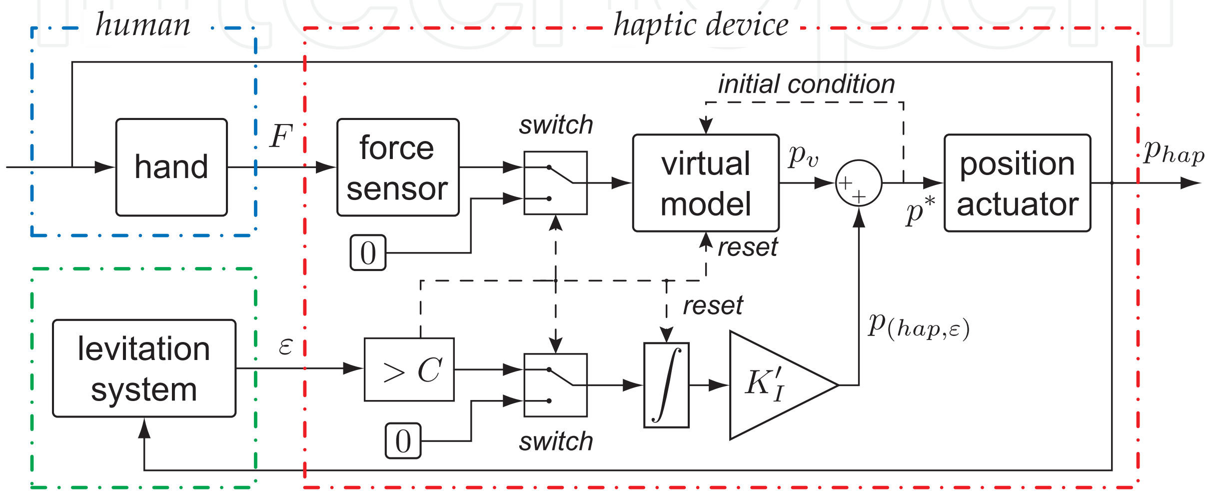


Fig. 14. Interaction between human, haptic device and electrostatic levitation

stiffness and outputting large forces. However, the strategy of admittance control is the inverse of impedance control as the haptic device measures the operator's force and gives a displacement based on the virtual model (force in, position out). This will require a modification on the implementation of the "Haptic Tweezer" concept.

Since the admittance control strategy is the inverse of admittance, the haptic contribution should also be inverted. Ideally that would mean that a force error is measured on the levitation system and a PI-controller adds a position signal to the virtual world output based on this force error. As in the levitation system itself, force is proportional to the air gap (in linearized case), this strategy should also work by substituting the levitation force error by the levitation position error. However, initial results were not satisfactory (unnatural feeling and damaging contact between object and levitator occurred) and the strategy for admittance controlled haptic devices had to be modified based on trial and error. Good results were achieved with the strategy as shown in Fig. 14.

The admittance control algorithm can be recognized in the upper part of the figure. The force from the operator is measured by a force sensor and this force is then sent to a virtual model. The virtual model calculates the position of the end-effector based on the effects acting on the object in the virtual model, such as damping, stiffness, and inertia. The position actuator gives the haptic position feedback p_{hap} that follows the reference position signal p^*.

The state of the electrostatic levitation system is indicated by levitation error ε. If the position error exceeds a certain threshold value C, it activates two switches that change the behavior of the total system. The first switch makes the input force to the virtual model zero, while the

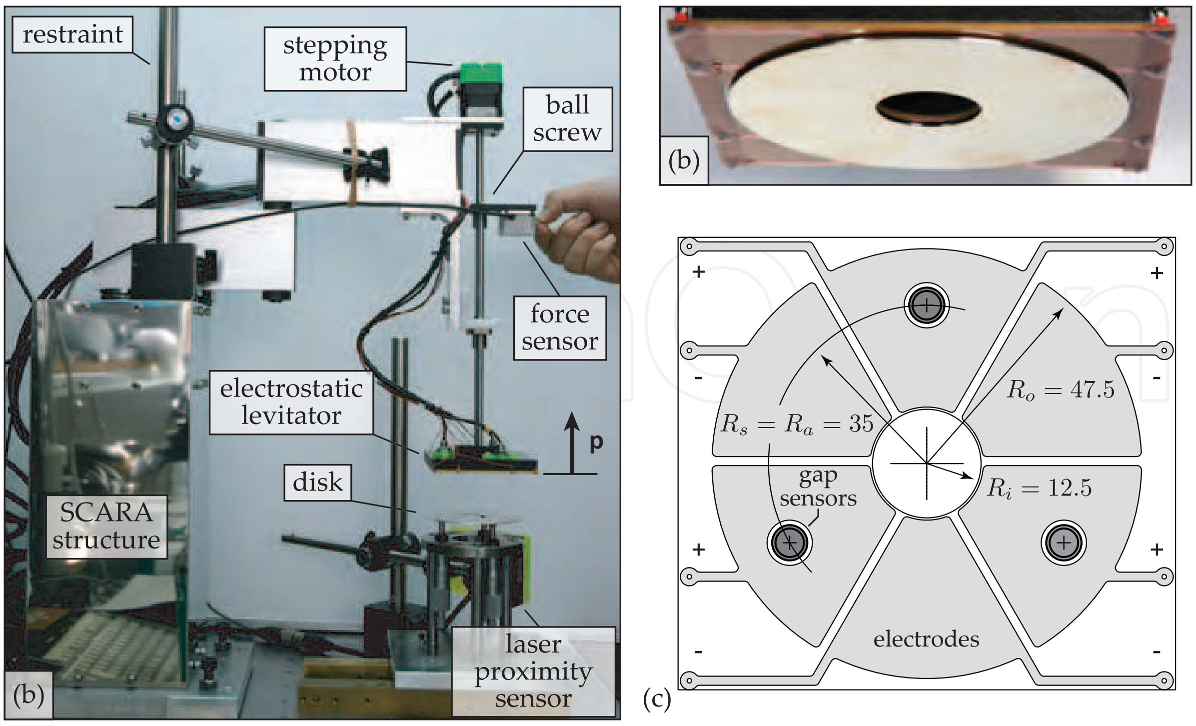


Fig. 15. (a) Prototype with electrostatic levitation and a SCARA-type haptic device. (b) The disk during stable levitation (air gap roughly 350 μm. (c) Details of the electrostatic levitator.

second switch allows the position error to pass through to an integrator. The threshold also sends a signal to the virtual model to reset any integrators inside the virtual model, and the results is a constant position output from the virtual model, which the operator experiences as he hitting a virtual wall. At the same time, the position error from the levitation system is integrated and added to the output of the virtual model as $p_{hap,\varepsilon}$. This minimizes the real levitation error ε as the end-effector with the electrostatic levitator moves up (positive p). When the error is again smaller than the threshold value C, the switches switch back to their previous value. To make sure that there are no discontinuities in the position signal that is sent to the position actuator, initial values for the virtual model are set at the moment of switching.

This strategy is further enhanced on two points to allow natural handling, which are not shown in Fig. 14 to avoid confusion. Firstly, the motion of the operator is automatically reduced when the levitator comes near the disk by using a high damping field, activated by a proximity sensor. Secondly, the switching criteria is extended to include the sign of force (positive/negative). That means that even if there is a levitation position error ($\varepsilon > C$), but there is a positive upwards force ($F > 0$), the position command p^*, will be entirely from the virtual model as the resulting motion will be upwards. This enhances the natural sensation to the operator.

6.2 Experimental setup

A general overview of the experimental setup is shown in Fig. 15, showing the complete prototype (a), the disk during stable levitation (b), and the details of the electrostatic levitator (c). An aluminium hard disk is used as the levitated object as it is freely available and reference literature is available (Jin et al., 1995). The haptic device is based on a SCARA-type robot (Padhy, 1992) and has three DOF, of which currently only one is actively controlled (vertical

Levitation		
Proportional gain z_c	K_{P,z_c}	$10 \cdot 10^6$ V/m
Integral gain z_c	K_{I,z_c}	$5 \cdot 10^6$ V/(m s)
Proportional gain θ_x, θ_y	$K_{P,\theta_x} = K_{P,\theta_y}$	$0.5 \cdot 10^6$ V/rad
Force-voltage relation	k_u	$2.8 \cdot 10^{-4}$ N/V
Force-air gap relation	k_z	-630 N/m
EstatLev stiffness	$k_{EstatLev}$	$2.2 \cdot 10^3$ N/m
Haptic Device		
Haptic integral gain	K'_I	10 s^{-1}
Mechanical stiffness	k	51 kN/m

Table 4. Control settings and other characteristics of electrostatic prototype

translation). More information on the development of this device can be found in (van West, Yamamoto & Higuchi, 2007b). For these experiments, the two rotational degrees of freedom are constraint to have only vertical motion. The input force is measured by a strain-gage load cell (Kyowa LVS-1KA, rated capacity: 10 N, force resolution: 50 mN) and the vertical displacement is generated by a direct motor drive ball screw (SiMB0802). The driving unit is a combination of a stepping motor with a ball screw directly connected to it, such that the need for a coupling is eliminated. As the lead screw is backlash-free, there is some friction in the mechanism. This friction however, will be eliminated by the admittance control loop up to the resolution of the force sensor. Furthermore, the position actuator is highly non-backdrivable, making it very suitable for admittance control.

The stepping motor is pulse-driven (max. 10 kHz) and the manufacturer guarantees no stepping out. Servo control is realized by feedback control on the pulses sent to the motor. The step resolution of the controlled system is set to 8 μm which fixes the maximum speed to 80 mm/s. As velocities in the virtual model can exceed this value, extra damping is automatically added to the virtual model when speed becomes larger than 75 mm/s.

A laser proximity sensor (Keyence LC2440) activates a high damping field when the distance between levitator and pick and place location becomes smaller than 2.5 mm by adding damping with a gradient of 50.000 Ns/m^2. For this experiment, the laser sensor has been mounted to the fixed world, but in the future it will be incorporated in the levitator to allow handling at any location. The nominal damping during normal moving is set to 4 Ns/m and the virtual mass is 1 kg. The haptic gain on the integral of the levitation error K'_I is 10 s^{-1}, set by trial and error.

The levitation air gaps are measured by three eddy-current displacement sensors (Keyence EX-800), which have a sensing range of 0 to 1 mm. The levitation system, virtual model and switching scheme are all integrated on the same digital signal processing (DSP) system, which is running at 20 kHz, with the controller settings as given in Table 4. Note that the Derivative gains (K_D) are zero as the air gap is so small that a natural damping exists and derivative gains are unnecessary. The reference gap is set to 350 μm and the bias voltage V_e is 920 V. The controller output is connected to four high voltage D.C. amplifiers (Trek 609C-6), which have an internal gain of 1000 and are limited on the control side to 1.6 kV in absolute value to prevent electric discharge.

6.3 Experimental results

The performance of this prototype is evaluated by performing a *picking up* and *placing* task. However, no comparison experiments are carried out as in fact it is nearly impossible for the human operator to hold the electrostatic levitator directly without losing the object, let alone performing a pick and place task. Performing the task with the haptic device, but *without* the haptic effect is too dangerous because of the high forces the haptic device can provide.

6.3.1 Picking up

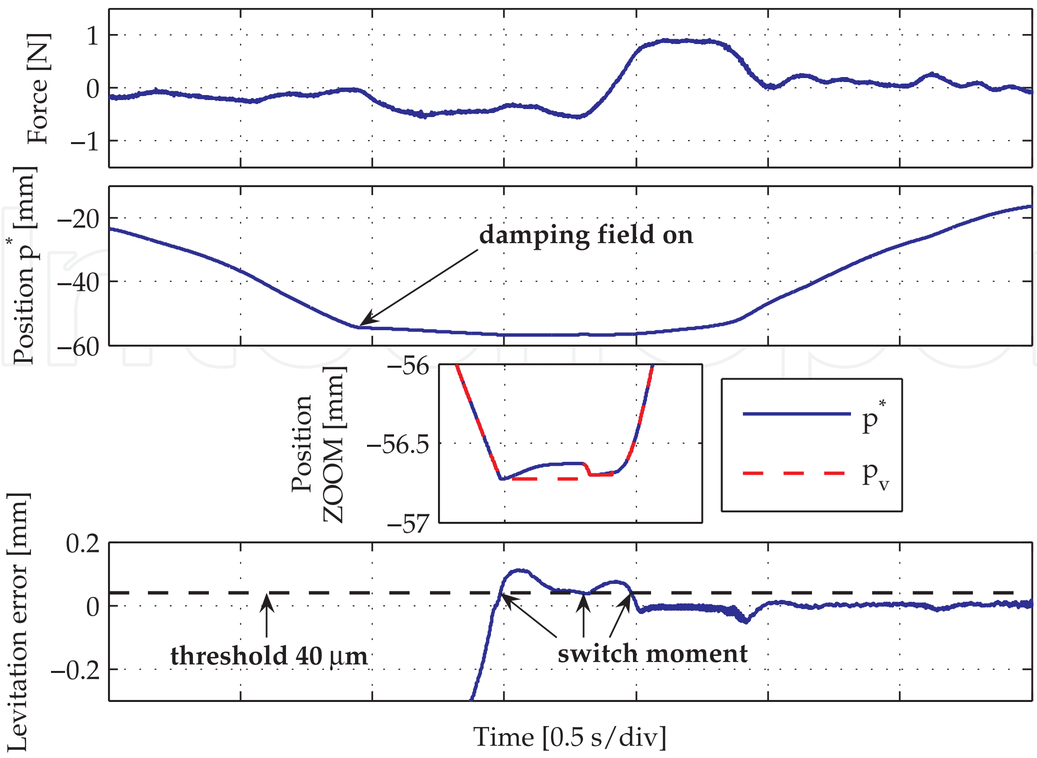
Details of a typical *picking up* task are shown in Fig. 16(a). The force exerted by the operator on the haptic device (force sensor) is shown in the top. A negative force will result in a downwards motion until the disk is picked up and it is followed by a positive force to move levitator and disk upwards. The motion that is sent to the position actuator (p^*) is shown in the two middle plots. The change of speed, resulting from the high damping field is indicated in the graph. To show the influence of the haptic contribution, which is the integral of levitation error to position signal p^* at the switching moment, a zoomed plot of p^* is given together with the output from only the virtual model p_v. The difference between the two plots is the added integral of levitation error $p_{hap,\varepsilon}$. The levitation error itself is plotted in the lowest plot together with the threshold value, such that the switching moments can be easily recognized.

The *picking up* task can be described in four steps. First, the operator moves down by applying a downward force on the haptic device. Downward motion occurs and as soon as it comes in sensing range of the laser sensing, the damping field slows down the motion. Second, the disk comes in sensing range of the levitation gap sensors and will “jump” to the nominal levitation air gap of 350 μm (levitation error is zero). Due to the downward speed of the motion, almost directly after the levitating, the disk touches the support location again, creating a positive levitation error. The switch is activated and resultantly, the position p^* is upwards even though the operator’s force is still a negative. This is experienced by the operator as touching a wall. Finally, a positive force from the operator will result in the upwards motion and picking up has been successful.

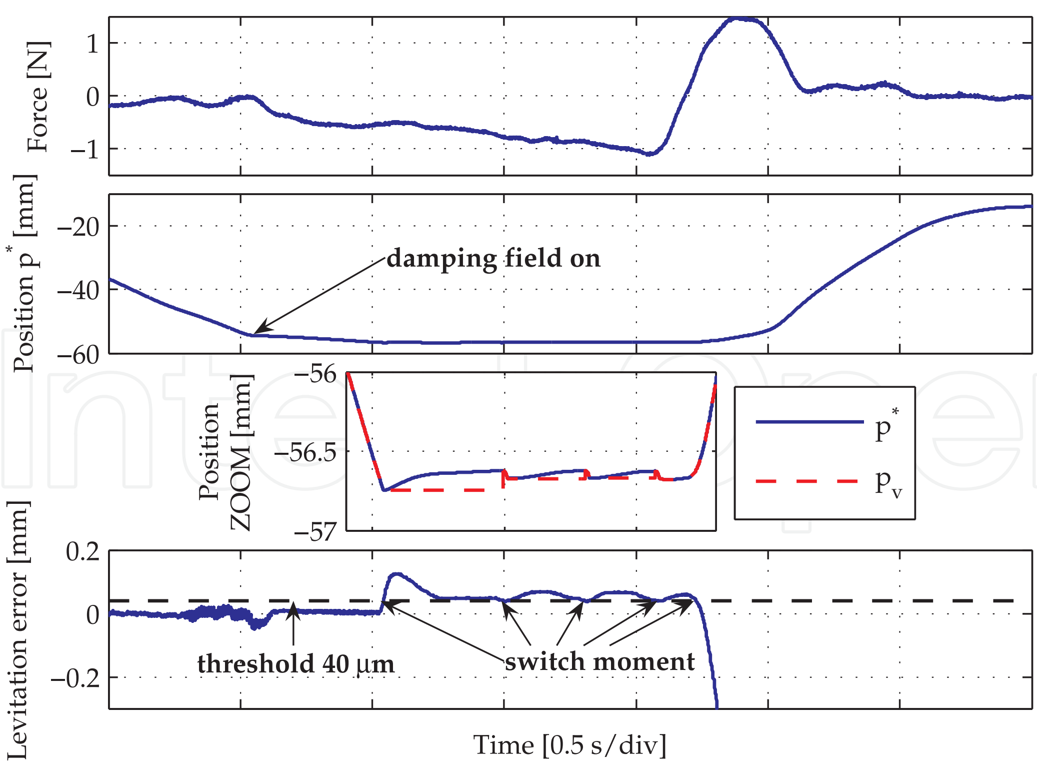
6.3.2 Placing

Details of a typical *placing* task are shown in Fig. 16(b), which follows the same structure as Fig. 16(a), with the operator’s force on the top, the position signal in the middle, and the levitation error on the bottom. The force and motion profile are very similar to the *picking up* task. A negative force from the operator moves the levitated disk down and it is slowed down by the damping field upon detection by the laser sensor. The contact moment can be clearly seen by looking at the levitation error as well as the switching moments that prevent the air gap to become too small. Multiple switching moments can be observed as in fact the operator is still exerting a negative (downward) force. The positive force from the operator will move the electrostatic levitator up, while the disk remains at the support location and placing has been successful.

The actual release of the object is the result of the levitation controller wind up (not shown in the figure) due to the integral gain K_I as described earlier. The integrator reduces the attractive force as long as there is a positive levitation error. If this error persists for some time, the controller output is influenced in such a way, that even if the error is relieved, re-levitation is no longer possible (van West et al., 2008). With this strategy, placing becomes more easy as it is realized automatically.



(a) Details of typical picking up



(b) Details of typical placing

Fig. 16. Manipulation using SCARA-type haptic device for electrostatic levitation handling

7. Conclusion

This research has proposed the concept of "Haptic Tweezer," which combines a haptic device with non-contact levitation techniques for intuitive and easy handling of contact-sensitive objects by a human operator. The levitation error of the levitated object is used as an input for the haptic device to minimize disturbances especially in the tasks of *picking up* and *placing*. The concept is evaluated by several prototypes of which two are described in this chapter, one using magnetic levitation and the haptic device PHANTOM Omni using an impedance controlled strategy, and a second prototype that uses electrostatic levitation and a SCRARA-type haptic device using the admittance control strategy. Experiments with the first prototype have showed that significant improvements can be realized through the haptic feedback technology. Not only the failure rates were reduced, but the manipulation time was faster indicating it is easier to perform the manipulation task with haptic assistance. The second prototype showed that the concept can also be successfully applied to handling objects with electrostatic levitation, which is more sensitive to disturbances than magnetic levitation and also has a much smaller levitation gap (350 μm). The haptic assistance makes it possible that a human operator can perform the tasks of *picking up* and *placing* of an aluminium disk which would not have been possible without any haptic assistance. Both cases demonstrate the potential of haptic assistance for real-time assisting in performing tasks like non-contact manipulation.

8. References

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S. & MacIntyre, B. (2001). Recent advances in augmented reality, *IEEE Computer Graphics and Applications* **21**(6): 34 – 47.

Azuma, R. T. (1997). A survey of augmented reality, *Presence: Teleoperators and Virtual Environments* **6**(4): 355–385.

Bettini, A., Marayong, P., Lang, S., Okamura, A. M. & Hager, G. D. (2004). Vision-assisted control for manipulation using virtual fixtures, *IEEE Transactions on Robotics* **20**(6): 953 – 966.

Bhushan, B. (2003). Adhesion and stiction: mechanisms, measurement techniques, and methods for reduction, *Journal of Vacuum Science & Technology B (Microelectronics and Nanometer Structures)* **21**(6): 2262 – 96.

Earnshaw, S. (1842). On the nature of the molecular forces which regulate the constitution of the luminiferous ether, *Trans. Camb. Phil. Soc.* **7**: 97–112.

Hayashibara, Y., Tanie, K., Arai, H. & Tokashiki, H. (1997). Development of power assist system with individual compensation ratios for gravity and dynamic load, *Proc. IEEE International Conference on Intelligent Robots and Systems IROS97*, pp. 640–646.

Jin, J., Higuchi, T. & Kanemoto, M. (1994). Electrostatic silicon wafer suspension, *Fourth International Symposium on Magnetic Bearings*, ETH Zurich, pp. 343 – 348.

Jin, J., Higuchi, T. & Kanemoto, M. (1995). Electrostatic levitator for hard disk media, *IEEE Transactions on Industrial Electronics* **42**(5): 467 – 73.

Kazerooni, H. (1996). The human power amplifier technology at the university of california, berkeley, *Robotics and Autonomous Systems* **19**(2): 179 – 187.

Kazerooni, H. & Steger, R. (2006). The berkeley lower extremity exoskeleton, *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME* **128**(1): 14 – 25.

Lee, H.-K., Takubo, T., Arai, H. & Tanie, K. (2000). Control of mobile manipulators for power assist systems, *Journal of Robotic Systems* **17**(9): 469 – 77.

Lin, H. C., Mills, K., Kazanzides, P., Hager, G. D., Marayong, P., Okamura, A. M. & Karam, R. (2006). Portability and applicability of virtual fixtures across medical and manufacturing tasks, *Proc. IEEE Int. Conf. Rob. Autom. ICRA06*, Orlando, Florida.

Morishita, M. & Azukizawa, T. (1988). Zero power control of electromagnetic levitation system, *Electrical Engineering in Japan* **108**(3): 111–120.

Nojima, T., Sekiguchi, D., Inami, M. & Tachi, S. (2002). The smarttool: A system for augmented reality of haptics, *Proc. Virtual Reality Annual International Symposium*, Orlando, FL, pp. 67 – 72.

Padhy, S. (1992). On the dynamics of scara robot, *Robotics and Autonomous Systems* **10**(1): 71 – 78.

Peshkin, M., Colgate, J., Wannasuphoprasit, W., Moore, C., Gillespie, R. & Akella, P. (2001). Cobot architecture, *IEEE Transactions on Robotics and Automation* **17**(4): 377 – 390.

Rollot, Y., Regnier, S. & Guinot, J.-C. (1999). Simulation of micro-manipulations: Adhesion forces and specific dynamic models, *International Journal of Adhesion and Adhesives* **19**(1): 35 – 48.

Rosenberg, L. B. (1993). Virtual fixtures: perceptual tools for telerobotic manipulation, *IEEE Virtual Reality Annual International Symposium*, Seattle, WA, USA, pp. 76 – 82.

Schweitzer, G., Bleuler, H. & Traxler, A. (1994). *Active Magnetic Bearings*, vdf Hochschulverlag AG an der ETH Zürich.

Taylor, R., Jensen, P., Whitcomb, L., Barnes, A., Kumar, R., Stoianovici, D., Gupta, P., Wang, Z., deJuan, E. & Kavoussi, L. (1999). a steady-hand robotic system for microsurgical augmentation, *International Journal of Robotics Research* **18**(12): 1201 – 1210.

van der Linde, R. & Lammertse, P. (2003). Hapticmaster - a generic force controlled robot for human interaction, *Industrial Robot* **30**(6): 515–24.

van West, E., Yamamoto, A., Burns, B. & Higuchi, T. (2007). Non-contact handling of hard-disk media by human operator using electrostatic levitation and haptic device, *Proceedings of the 2007 IEEE/RSJ International Conference on Intelligent Robots and Systems IROS'07*, San Diego, CA, USA, pp. 1106–11.

van West, E., Yamamoto, A. & Higuchi, T. (2007a). The concept of "haptic tweezer", a non-contact object handling system using levitation techniques and haptics, *Mechatronics* **17**(7): 345–356.

van West, E., Yamamoto, A. & Higuchi, T. (2007b). Development of scara-type haptic device for electrostatic non-contact handling system, *Journal of Advanced Mechanical Design, Systems, and Manufacturing* **2**(2): 180–190.

van West, E., Yamamoto, A. & Higuchi, T. (2008). Automatic object release in magnetic and electrostatic levitation systems, *Precision Engineering* **33**: 217–228.

Woo, S. J., Jeon, J. U., Higuchi, T. & Jin, J. (1995). Electrostatic force analysis of electrostatic levitation system, *Proceedings of the 34th SICE Annual Conference*, Hokkaido, Japan, pp. 1347–52.

Advances in Haptics

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Haptic interfaces are divided into two main categories: force feedback and tactile. Force feedback interfaces are used to explore and modify remote/virtual objects in three physical dimensions in applications including computer-aided design, computer-assisted surgery, and computer-aided assembly. Tactile interfaces deal with surface properties such as roughness, smoothness, and temperature. Haptic research is intrinsically multi-disciplinary, incorporating computer science/engineering, control, robotics, psychophysics, and human motor control. By extending the scope of research in haptics, advances can be achieved in existing applications such as computer-aided design (CAD), tele-surgery, rehabilitation, scientific visualization, robot-assisted surgery, authentication, and graphical user interfaces (GUI), to name a few. Advances in Haptics presents a number of recent contributions to the field of haptics. Authors from around the world present the results of their research on various issues in the field of haptics.