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Using Magnetic Levitation for Haptic Interaction

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1. Introduction

Magnetic levitation as a means of motion and force/torque control can provide many advantages for high-fidelity haptic interaction, as compared to motorized linkage and cable actuation. Impedance-based haptic interface devices function both as force display devices, generating forces and/or torques to be felt by the user, and as input devices, sensing the motions imparted by the user to the device. The realism of the haptic interaction is related to the performance of these two functions, which can be quantitatively measured by their position and force accuracy and response times.

Magnetic levitation devices have been able to provide very high force & position control bandwidths, resolution, and impedance ranges for haptic interaction through a grasped tool handle. Only one moving part is required to provide precise, responsive, 6 degree-of-freedom frictionless motion with force and torque feedback to interact with a simulated or remote environment. With no friction from contacts with actuation or sensing mechanisms, magnetic levitation devices are ideally backdriveable and dynamic nonlinearities such as cogging and backlash are eliminated.

The small motion ranges of current tabletop magnetic levitation devices in translation and rotation have been a severe limitation on the size and type of interactive environments and tasks, however. Small motion ranges of magnetic levitation devices are due to a combination of narrow magnetic field gaps and linearized magnetic actuation models which are only valid in a neighborhood of a given setpoint. As a result, magnetic levitation haptic interfaces which have been previously developed focus on fingertip-scale motions, and provide variable indexing, rate control, and scaling methods through software to simulate interaction with larger environments.

The mass and rotational inertia perceived by the user as the haptic interface device is manipulated affects the realism of haptic interaction, as well as the position control bandwidths of the device. The transparency of haptic interaction is improved when the encountered mass and inertia are minimized.

We have developed two different magnetic levitation devices which provide unprecedented ranges of motion in both translation and rotation to a levitated handle to be used for tool-based haptic interaction. The first device levitates a handle attached to a thin spherical shell of flat coils suspended in permanent magnet fields using Lorentz forces. A novel coil type and magnet configuration provides double the translation and triple the rotation ranges of previous Lorentz levitation haptic devices.

The second device uses a planar array of cylindrical coils to levitate a platform of one or more magnets. By using redundant control methods and an experimentally measured high resolution model of the forces and torques generated on the levitated magnets from each coil, the translation range of the magnet in horizontal directions and its rotation in all directions can be extended indefinitely. These new devices permit fuller wrist and forearm motions of the user for haptic interaction rather than the fingertips-only motions provided by previous magnetic levitation haptic interface devices. Design, analysis, and control methods are presented with measured haptic performance characteristics and haptic interaction task results from both devices.
The following section surveys current technology background in magnetic levitation and grasped haptic interaction devices actuated by motorized linkages and/or cables. Section 3 describes early Loretz force magnetic levitation devices developed for haptic interaction by Hollis, Salcudean, and Berkelman. Sections 4 and 5 describe our current development of a Lorentz force magnetic levitation haptic interface device with a new magnet and coil configuration to increase its translation and rotation ranges and a levitation system using an array of cylindrical coils to levitate one or more disk magnets, followed by a future work and conclusion section.

2. Research Background

2.1 Magnetic Levitation Systems

Magnetic levitation systems can provide advantages for applications in manipulation (Oh et al., 1993; Khamesee & Shameli, 2005) fine positioning (Kim & Trumper, 1998; Kim et al., 2004), and haptic interaction (Hollis & Salcudean, 1993; Berkelman & Hollis, 2000). Surveys of magnetic levitation technology for rail transportation are given in (Lee et al., 2006) and for magnetic bearings in (Schweitzer et al., 1994). Other existing systems (Wang & Busch-Vishniac, 1994; Lai et al., 2007; Robertson et al., 2005; Zhang & Menq, 2007) also typically have ranges of motion which are limited however to a small fraction of the dimensions of the levitated body in most or all directions, and to rotation angles of less than 20 degrees.
High frequency feedback control is necessary to stabilize magnetic levitation. Non-contact position sensing for feedback control of magnetic levitation can be provided by optical methods using LED markers and position sensing photodiodes, Hall effect magnetic sensing (Gohin et al., 2007), or by laser interferometry which can provide submicrometer precision position sensing.
Lorentz force levitation was initially developed for compliant assembly robotic wrists (Hollis and Salcudean, 1993). Hollis and Salcudean pioneered the use of Lorentz force actuation from currents in flat racetrack-shaped coils suspended between horseshoe-shaped magnet assemblies, producing forces independent of coil positions provided that magnetic fields are constant.
A large range of motion levitation system for small magnets using multiple permanent magnets, pole pieces, and actuation coils to control magnetic fields is described in (Khamesee & Shameli, 2005). A gripper has been added to this system for magnetic levitation micromanipulation (Craig & Khamesee, 2007), however the spatial rotation of the magnet is uncontrolled.
Spherical motors (Yan et al., 2006; Chirikjian & Stein, 1999) have been developed to control spatial orientation of a rigid body using magnets and coils, yet these are supported by

bearings and not levitated or controlled in position. A dipole model for simplified magnetic field torque computations in spherical motor is presented in (Lee et al., 2009).
The previous work most closely related to our current research on levitation of cylindrical magnets using a coil array was by (Groom & Britcher, 1992), who carried out extensive analysis of electromagnetic actuation, rigid body dynamics, and feedback control methods for levitation with large rotations. Owing to limitations in position and orientation sensing, implementation was limited to small motions however. Baheti and Koumboulis (Baheti, 1984; Koumboulis & Skarpetis, 1996) have also carried out related work on magnetic suspension and balance systems for models in wind tunnels.

2.2 High-Fidelity Haptic Interface Devices

Haptic interface devices are typically actuated by DC motors through linkages and low-friction drivetrains such as belts and cables. As the motors produce torque directly, it is straightforward to generate haptic forces to the user given the kinematics of the linkage. High fidelity haptic interaction with position control bandwidths greater than 100 Hz may be realized by designing the linkage to be as stiff and lightweight as possible, with minimal joint friction and backlash. Parallel linkage designs can be made particularly stiff and lightweight, although joint friction may be more significant. Many of these devices provide 3 DOF force feedback only, as this is sufficent for haptic interaction at a single "fingertip" point and a 6 DOF mechanism must add complexity, mass, and friction which reduce its dynamic performance.
The most widely used haptic interface devices are the *Phantom* devices from Sensable Technologies Inc (Massie & Salisbury, 1994). In these devices the user grasps a pen which is mounted on a gimbal to a counterweighted, cable-driven parallelogram linkage. 3 DOF force feedback and and 6 DOF force and torque feedback models of various sizes and configurations are available. The *Delta* haptic device (Grange et al., 2001) is based on 3 parallel link sets and has similar properties, and is also commercially available in 3 and 6 DOF feedback versions.
The *Pantograph* (Hayward et al., 1994) design maximizes the control bandwith obtainable from a 2 DOF planar parallelogram linkage. The *Freedom* 6/7 (Hayward, 1995) devices provide 6 and 7 DOF with an attached gripper using a complex linkage with cable drives.

3. Racetrack Coil Lorentz Force Magnetic Levitation Haptic Interfaces

3.1 IBM Magic Wrist

The *Magic Wrist* was adapted for haptic interaction by fixing it to a stationary base rather than a robotic arm (Berkelman et al., 1995), as shown in Figure 1. This device provided high control bandwidths, position resolution, and stiff haptic contacts, but its motion range is limited to less than 10 mm and 10 degrees rotation. The levitated coils in this device are embedded in a hexagonal box.

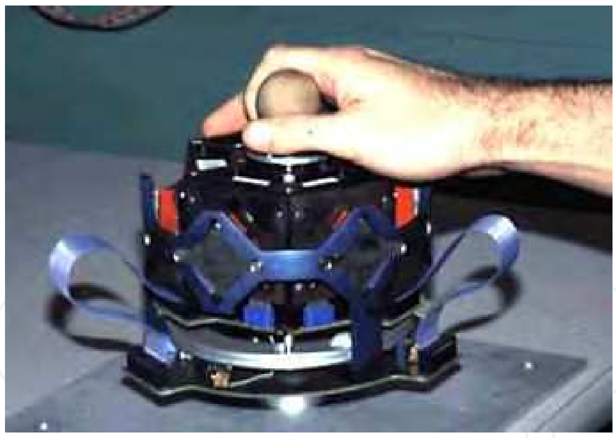

Fig. 1. IBM Magic Wrist used as haptic interface device

3.2 UBC Teleoperation Master and Powermouse

The *Teloperation Master* developed at the University of British Columbia (Salcudean et al., 1995) has a similar size and motion range as the Magic Wrist, yet has a novel magnet and coil configuration. Its structure, with the grasped cover removed, is shown in Figure 2(a). The *Powermouse* (Salcudean & Parker, 1997) is a smaller desktop device, with reduced mass and a small motion range adaped for fingertip interaction. Its levitation coils are arranged on the faces of a cube embedded inside the housing of the device shown in Figure 2(b).

3.3 CMU / Butterfly Haptics Maglev Haptic Interface

Another Lorentz force magnetic levitation haptic interface device was developed at Carnegie Mellon by Berkelman and Hollis (Berkelman & Hollis, 2000) , with the coil and magnet configuration and position sensing system modified to provide a large increase in the ranges of motion in both translation, at 25 mm, and rotation at 15 degrees. The main factor in the motion range increase was to embed large actuator coils tightly together in a thin hemispherical shell, with the interaction handle mounted at the center. The top of the device and its use with a graphically displayed environment on a PC are shown in Figure 3.

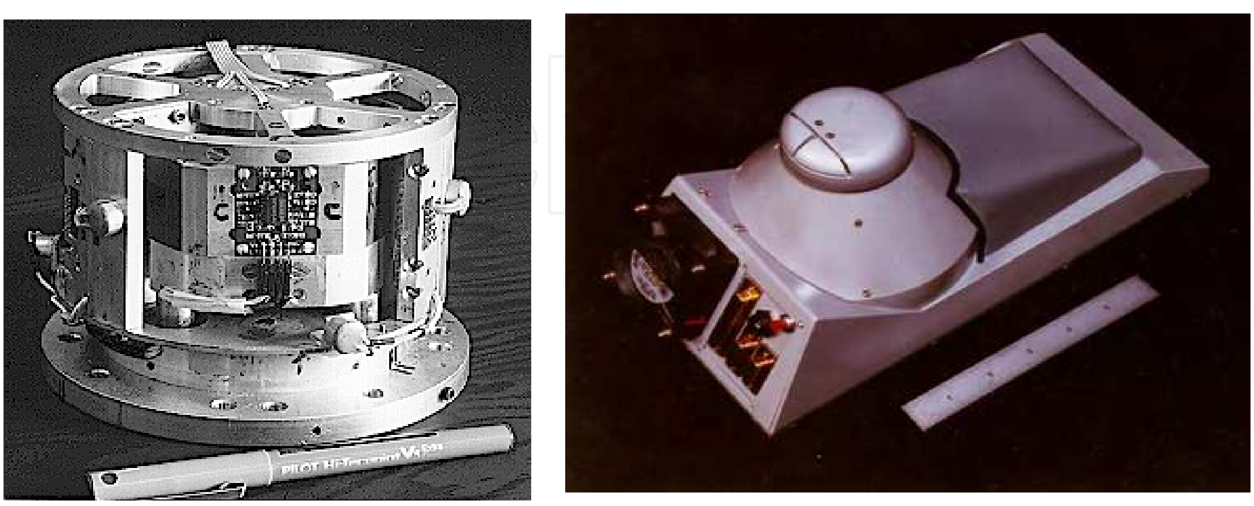

Fig. 2. (a) UBC Teleoperation Master, (b) UBC Powermouse

Fig. 3. Carnegie Mellon University Prototype (a) Levitated Handle Grasped by User, (b) Interaction with Simulated Environment

A commercial successor to this design, with improved position sensing feedback, a lighter, stiffer levitated hemisphere shell, and with a software programming interface, is currently produced by Butterfly Haptics LLC. At least 10 devices are in use in several different research labs composing a maglev haptic consortium.

4. Double Coil Layer Lorentz Magnetic Levitation Design

4.1 Design

Our first extended range magnetic levitation design is a Lorentz levitation device with coils on a spherical shell and a user handle mounted at the center of the shell, as in the Carnegie Mellon Lorentz devices. This device uses a novel coil shape, magnet configuration, and arranges the coils in two layers so that the magnetic field gap widths can be doubled at approximately the same field intensity as before and the coil areas can be increased many times more on a shell of approximately the same radius, resulting in a doubling of the translation range and a tripling of the rotation range in all directions. The basic design is described in more detail in (Berkelman, 2007) and shown in Figure 4. Instead of using racetrack-shaped coils in which the coil windings follow oval paths, a new coil shape shown in Figure 5(a) is used in which the windings follow straight paths across the centers of the coils, and curved return paths around the periphery of the round coils. This allows the coils to be arranged in two layers as in Figure 5(b), with the straight wires across the centers of the coils orthogonal to one another. In this arrangement, the areas of the coils can be increased considerably without increasing the radius of the spherical shell, and each pair of layered coils requires only two magnets to generate their shared magnetic field. Large, curved iron pole pieces pass above and around the levitated coil assemblies to form a magnetic flux path from one magnet to the other on the opposite sides of each gap. The centers of the coil pairs are arranged at 0, 120, and 240 degrees around the circumference at an angle of 35 degrees below the horizontal plane, on a spherical surface with a 125 mm radius, and each coil spans a solid angle of 90 degrees. The effective solid angle of each coil is reduced to approximately 70 degrees due to the width of the magnets and the return

paths of the wires around the edges of the coils and the magnet gaps are 53 mm, so that the device can provide a motion range of 50 mm in translation and approximately 60 degrees in rotation in all directions.
As the translation range is approximately double and the rotation range is triple that of previous levitated haptic interaction devices, the workspace volume is actually increased by a factor of 8 and the rotation space by a factor of 27. The increased motion range

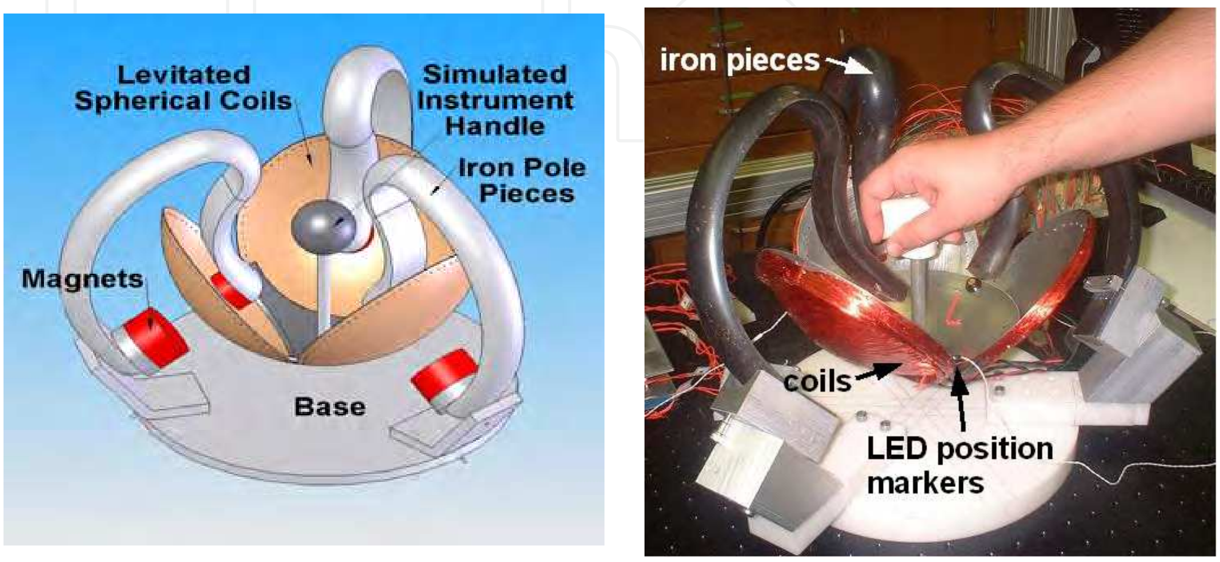

Fig. 4. Extended motion range spherical shell Lorentz force magnetic levitation device (a) Design, (b) device as fabricated

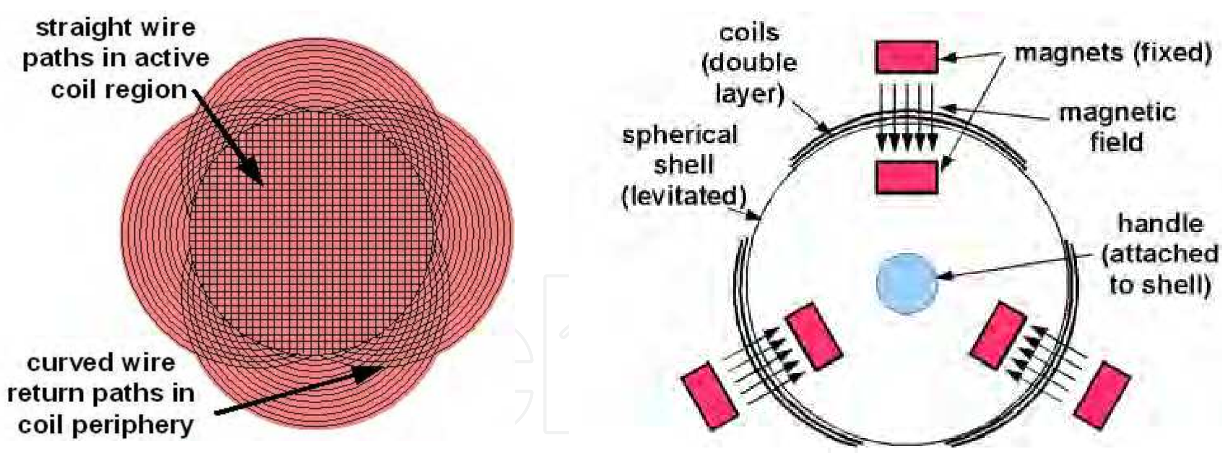

Fig. 5. (a) Double layer circular coil wire paths, (b) Magnet and double coil configuration

of the new device is not merely an incremental improvement, but enables a qualitatively much greater variety of interactive tasks to be simulated as the increased range is comparable to the full range of human wrist movement, whereas previous haptic levitation devices could accommodate fingertip motions only. For example, common manual manipulation tasks such as turning doorknobs, keys, and hexagonal nuts and screwheads can be realistically haptically simulated with the new device, and 60 degrees of rotation and 50 mm of translation is sufficient to simulate many tasks in minimally invasive surgery (Rosen et al., 2002).

The force generated by each coil can be modelled as a single force vector at the center of each coil, and one coil in each pair generates vertical and the other generates horizontal forces. The magnitude of the force generated by each coil is approximately 3.0 Newtons/Amp. With the coil center locations at:

$$r_{1,2} = 0.125\begin{bmatrix}\cos(35)\\0\\-\sin(35)\end{bmatrix},\quad r_{3,4} = 0.125\begin{bmatrix}\cos(120)\ \cos(35)\\\sin(120)\ \sin(35)\\-\sin\ (35)\end{bmatrix},\quad r_{5,6} = 0.125\begin{bmatrix}\cos(240)\ \cos(35)\\\sin(240)\ \cos(35)\\-\sin\ (35)\end{bmatrix} \tag{1}$$

in m, and the forces generated by each coil at:

$$f_1 = 3.0\begin{bmatrix}\sin(35)\\0\\\cos(35)\end{bmatrix}i_1,\quad f_2 = 3.0\begin{bmatrix}0\\1\\0\end{bmatrix}i_2,\quad f_3 = 3.0\begin{bmatrix}\cos(120)\ \ \sin(35)\\\sin(120)\ \ \sin(35)\\\cos(35)\end{bmatrix}i_3,$$

$$f_4 = 3.0\begin{bmatrix}-\sin(20)\\\cos(35)\\0\end{bmatrix}i_4,\quad f_5 = 3.0\begin{bmatrix}\cos(240)\ \ \sin(35)\\\sin(240)\ \ \sin(35)\\\cos(35)\end{bmatrix}i_5,\quad f_6 = 3.0\begin{bmatrix}-\sin(240)\\\cos(240)\\0\end{bmatrix}i_6, \tag{2}$$

in Newtons, with angles in degrees, then the current to force and torque vector transformation matrix can be given as:

$$\begin{bmatrix}f_x\\f_y\\f_z\\\tau_x\\\tau_y\\\tau_z\end{bmatrix} = \begin{bmatrix}f_1 & f_2 & \cdots\\r_1\times f_1 & r_2\times f_2 & \cdots\end{bmatrix}\begin{bmatrix}i_1\\i_2\\i_3\\i_4\\i_5\\i_6\end{bmatrix} \tag{3}$$

to relate currents in A to forces in N and torques in N-m. When the sphere radius and the force magnitudes are normalized to 1 to compensate for differences in force and torque units, the condition number of the transformation matrix is 3.7, indicating that the matrix is invertable and forces and torques can be efficiently generated in all directions without requiring excessively larger coil currents for some directions.

4.2 Analysis and Fabrication

Electromagnetic finite element analysis was performed to find magnet shapes and dimensions to concentrate and maximize magnetic fields necessary for levitation. This analysis indicated that the minimum field strength in between magnets is approximately 0.25 T, which is expected from experience (Berkelman & Hollis, 2000) to be sufficient for levitation and high-fidelity haptic interaction. The mass of the fabricated levitated body is 1200 g; by fabricating new coils using aluminum wire and using a more lightweight support structure we aim to reduce the levitated mass to 500 g or less. In Figure 4(b), the iron pole pieces on two of the magnet assemblies have been rotated about the magnet axes by approximately 30 degrees to provide more ergonomic access for the user to more easily grasp the levitated handle without affecting the magnetic fields or the range of motion of the device.

4.3 Experimental Results

A sample large scale vertical step input motion trajectory for the free-floating levitated coils in the vertical direction is shown in Figure 5. The control gains used were as follows:

	translation	rotation
Kp	2.0 N/mm	0.0875 N-m/degree
Kd	0.01 N-sec/mm	0.00035 N-m-sec/degree

As these are very preliminary results, it is expected that more careful modeling, calibration, and signal processing will result in considerable increases of the maximum stable gains and a more damped response.

Regarding the positioning accuracy of the levitated bowl and the stiffness of the coil structure, it is notable that any flexion of the coils from high actuation forces would not affect the position accuracy of the manipulation handle, as the position sensing feedback is from LED markers close to the center of the structure, which is reinforced with an additional layer of aluminum and a collar around the base of the handle. Furthermore, for haptic interaction applications, absolute position accuracy of the device is not as critical as the incremental position and force accuracy and control bandwidths to the perceived fidelity of the haptic interaction.

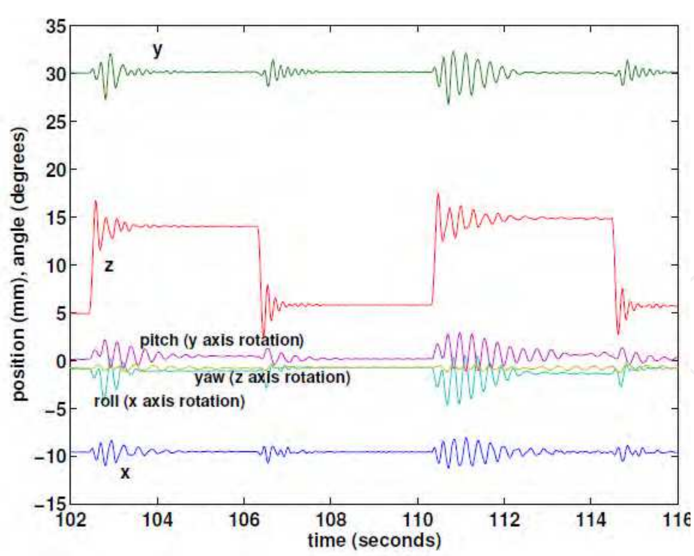

Fig. 6. Vertical step response results for new Lorentz levitation device

5. Magnet Levitation by Planar Array of Cylindrical Coils

5.1 Design

A redundant actuation method was used to levitate a single magnet by combining actuation forces and torques from more than 5 coils at a time. The potential advantages of redundant actuation compared to selections of coil subsets at each magnet position are that the maximum required coil currents for levitation may be reduced by distributing the generation of lifting forces over more coils, and discontinuous force disturbances due to measurement and position errors as coil currents are abruptly switched on and off during motion trajectories can be avoided. Sixteen coils of 25 mm diameter, 30 mm height, and 1000 windings are currently used, providing a motion range of approximately 100x80x30 mm with potentially unlimited tilt range. Rotation about the axis of a single disk magnet cannot be controlled due to its radial symmetry, so single magnet platform levitation leaves this yaw angle uncontrolled. The array levitation control methods, design, and initial results are described in further detail in (Berkelman & Dzadovsky, 2008). The levitated mass is approximately 125 g.

5.2 Control

To determine the model of force and torque generation between a single magnet and coil, an experimental setup of motion stages and a force sensor was used as in Figure 7(a). Although it is possible to obtain a force and torque generation model either analytically (as described in [5]) or from electromagnetic finite element analysis, in this case it is simpler and faster to obtain the model experimentally, and furthermore the effects of variations in the magnet material and its magnetization are accounted for directly.

The 6 force and torque elements generated between the magnet and coil were recorded at 1 mm intervals of vertical and radial separation and 30 degree angular intervals, resulting in the force and torque data partially shown in shown in Figure 7(b). The forces and torques generated by each coil were found to be independent and proportional to each coil current to a very close approximation, allowing the current to force and torque transformation to be represented in linear matrix form at any magnet position and orientation. This data was used to calculate the current to force and torque transformation for single magnet levitation. Defining the angle from each coil center i to the magnet center in the horizontal plane as ψ_i , the transformation from currents to forces and torques is as follows:

$$\begin{bmatrix} f_x \\ f_y \\ f_z \\ \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = \begin{bmatrix} \cos(\psi_1) f_x(r_1, z, \phi, \theta_i) - \sin(\psi_1) f_y(r_1, z, \phi, \theta_i) & \ldots \\ \sin(\psi_1) f_x(r_1, z, \phi, \theta_i) + \cos(\psi_1) f_y(r_1, z, \phi, \theta_i) & \ldots \\ f_x(r_1, z, \phi, \theta_i) & \ldots \\ \cos(\psi_1) f_x(r_1, z, \phi, \theta_i) - \sin(\psi_1) f_y(r_1, z, \phi, \theta_i) & \ldots \\ \sin(\psi_1) f_x(r_1, z, \phi, \theta_i) + \cos(\psi_1) f_y(r_1, z, \phi, \theta_i) & \ldots \\ f_x(r_1, z, \phi, \theta_i) & \ldots \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ \ldots \end{bmatrix} \qquad (4)$$

where z is the levitation height of the magnet center above the coil plane, and r_i is the horizontal distance from the center of the coil i to the center of the magnet. Since the coil forces

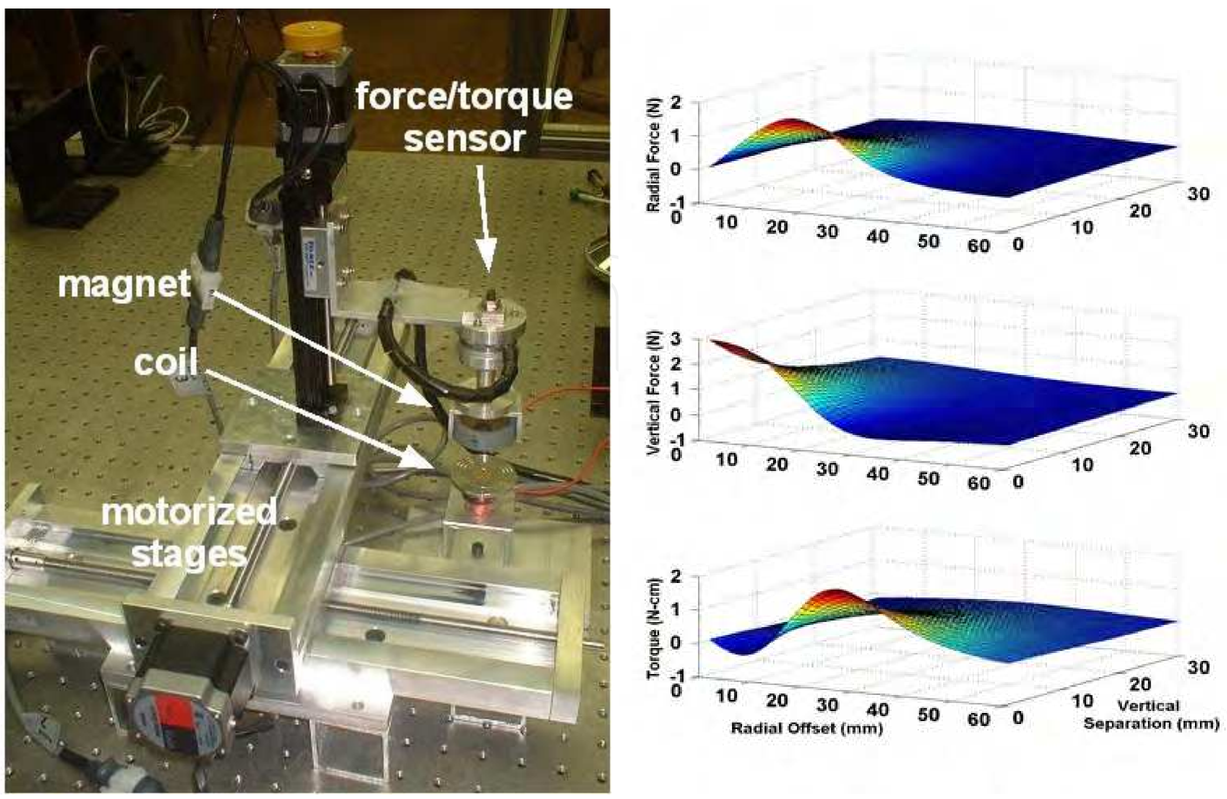

Fig. 7. (a) Motion stage and force/torque measurement setup, (b) Radial force, vertical force, and torque generated on magnet by coil with 1.0 Ampere current

and torques are measured at discrete values of θ, cubic interpolation is used to estimate the values of the continuous functions.

For 6 degree of freedom controlled levitation of platforms with multiple disk magnets, additional terms must be added due to the **r**×**f** torques from magnet forces **f** generated at a distance **r** from the center of mass of the levitated platform; it is these transformation terms which enable generation of τ_z torques to control the yaw angle.

As forces and torques are both produced in 3 dimensions, and there are 16 coils in the current setup, each resulting transformation matrix is 6x16 elements. This rectangular matrix is kinematically redundant, as the number of actuators is greater than the DOF to be controlled. For redundant systems in general, the Moore-Penrose pseudoinverse $\mathbf{A}^{+}$ of **A** (Moore, 1920; Penrose, 1955) can be used to calculate actuation currents $\mathbf{I} = \mathbf{A}^{+}\mathbf{F}$ with the lowest sum of squared currents for levitation control, adapting control methods developed for redundant actuation velocity control and execution of subspace tasks as described in (Nenchev, 1992; Baillieul, 1987). In our system however, the pseudoinverse of the transformation matrix cannot be directly inverted to produce the coil currents to produce a desired set of forces and torques, as no combination of coil currents can produce any torque on the magnet about its principal axis. For 5 DOF levitation control at arbitrary orientations, the torque vectors in the transformation matrices can rotated so that one of the torque directions is aligned with the magnet axis, and the row corresponding to these torques is reduced to approximately zero. This row can then be eliminated from the transformation matrix, and the pseudoinverse of the resulting reduced 5x16 transform matrix can then be

used to calculate coil currents to generate two torques perpendicular to the axis of the magnet to control its orientation while leaving the rotation of the magnet about its principal axis uncontrolled.
The force/torque to current transforms are precalculated to the closest 1.0 mm in translation and 30 degrees in orientation, and stored in a lookup table for use during realtime control.
Linear interpolation of the measured force and torque data described previously is used online for control, as the distance and angle from each coil to the magnet are not restricted to 1 mm and 30 degree intervals. Numerical computation software was used for the calculation of the force/torque to current transformation lookup tables.
Condition numbers of the transformation matrix across the motion plane are shown for a horizontal magnet orientation in Figure 8(a) and a vertical orientation in Figure 8(b) at a 25 mm levitation height. The locations of the 16 coil centers are indicated by asterisks '*', these are arranged in a hexagonal configuration with a spacing of 35 mm. The transformation condition numbers are greatest directly above the coil centers because the horizontal force and torque torque generation capabilites of the coil underneath are zero although the vertical force generation efficiencies are maximized at these locations.

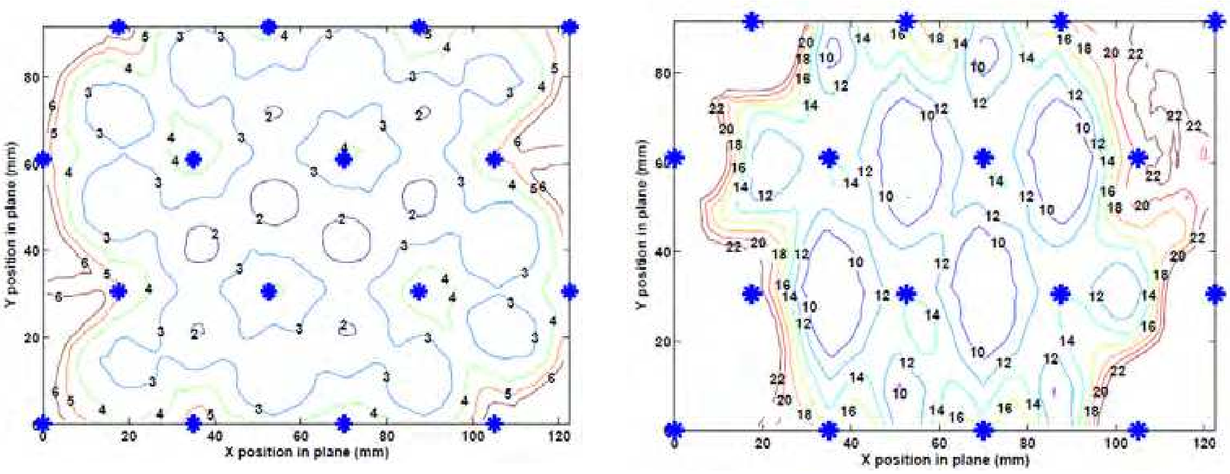

Fig. 8. Coil current to force/torque vector transformation matrix condition numbers, (a) Horizontal orientation, (b) vertical orientation

5.3 Results and Discussion

Using the system and methods described, we have realized stable levitation with 5 DOF control of a single disk magnet, as shown in Figure 9(a), and 6 DOF control of a magnet pair shown in Figure 9(b). A single levitated magnet may be embedded in a computer mouse shell for user interaction, as shown in Figure 10(a), and a single magnet may be levitated in any orientation by fixing 12 position markers to the levitated body oriented on the faces of a dodecahedron, so that at least 3 markers are visible to the position sensor at all times, as shown in Figure 10(b).

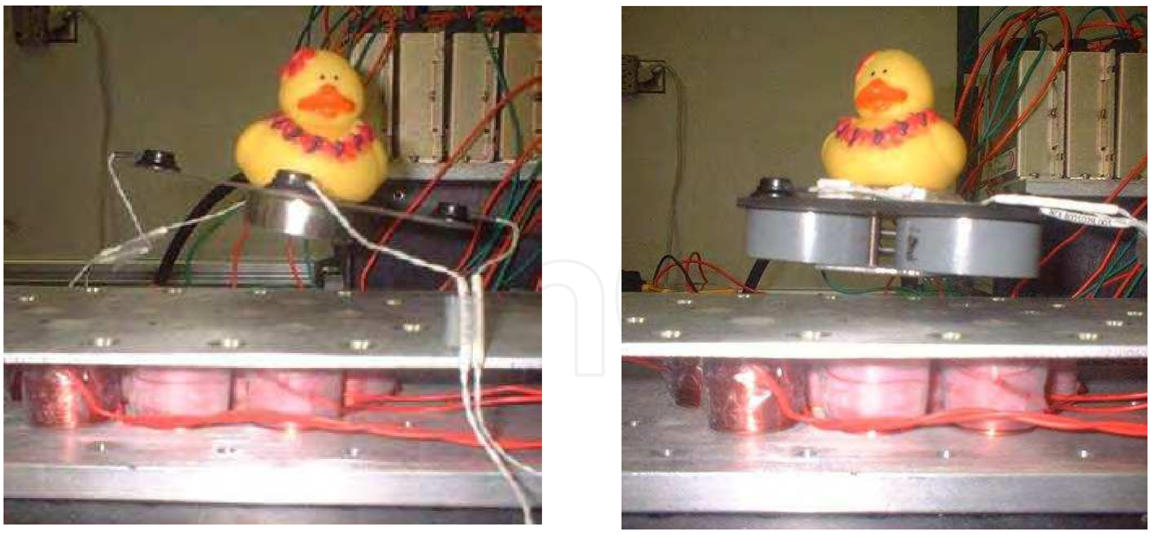

Fig. 9. (a) 5 DOF motion control with single disk magnet, (b) 6 DOF motion control

Large scale motion trajectories from a single free-floating levitated magnet are shown in Figure 11. The control gains used were as follows:

	translation	rotation
K_p	0.2 N/mm	5.25 N-mm/degree
K_d	0.002 N-sec/mm	0.0525 N-mm-sec/degree

The position control bandwidths of the system are limited by the maximum stable proportional gain, or stiffness of the controller, this gain is limited in turn by the resolution and noise level of the position sensor and the update rate of the controller. Initial levitation of two magnet platforms has also been demonstrated for 6 degree-of-freedom levitation control including yaw rotations.

6. Future Work and Conclusions

The planar array levitation system has greater potential for further expansion of its motion range in horizontal directions and rotations in all directions, but it is less efficient than the Lorentz levitation device, which can generate higher forces and torques without overheating. Each of the two systems will be interfaced to publically available haptic interaction software such as *Chai3d* and *H3D* to evaluate user perception and task performance using the devices.

Further development to be undertaken for each system includes modeling of the magnetic field variations in the Lorentz force device for better control performance, and modeling of magnetic actuation at any rotation angle for the planar system. Coils with iron cores will be used for more efficient actuation.

The two described magnetic levitation systems each provide greater motion ranges than any other previous magnetic levitation device for haptic interaction. The magnetic levitation systems and methods described are part of a larger research effort to investigate and develop magnetic levitation for high-fidelity haptic interaction.

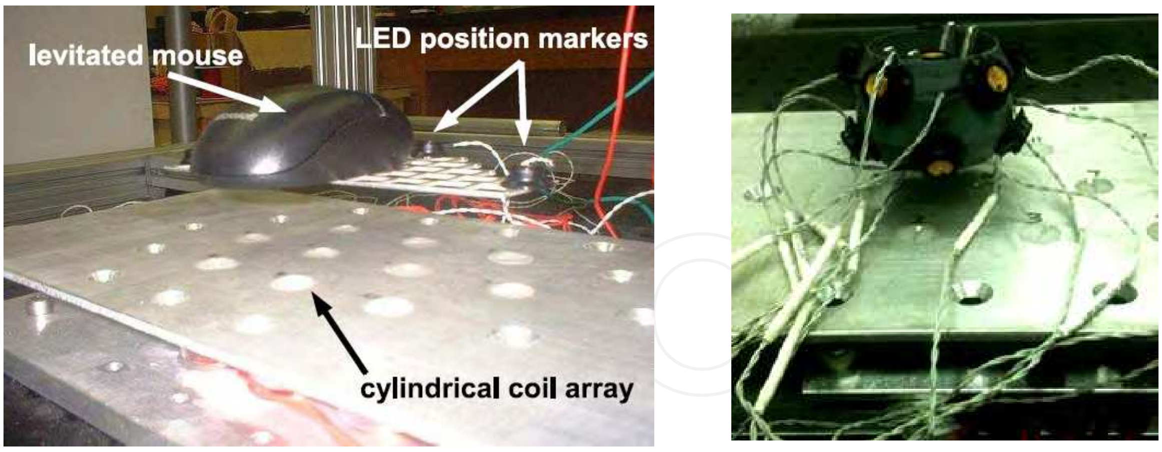

Fig. 10. (a) Levitated mouse with embedded magnet for haptic interaction, (b) 12 marker levitated body for levitation at any orientation

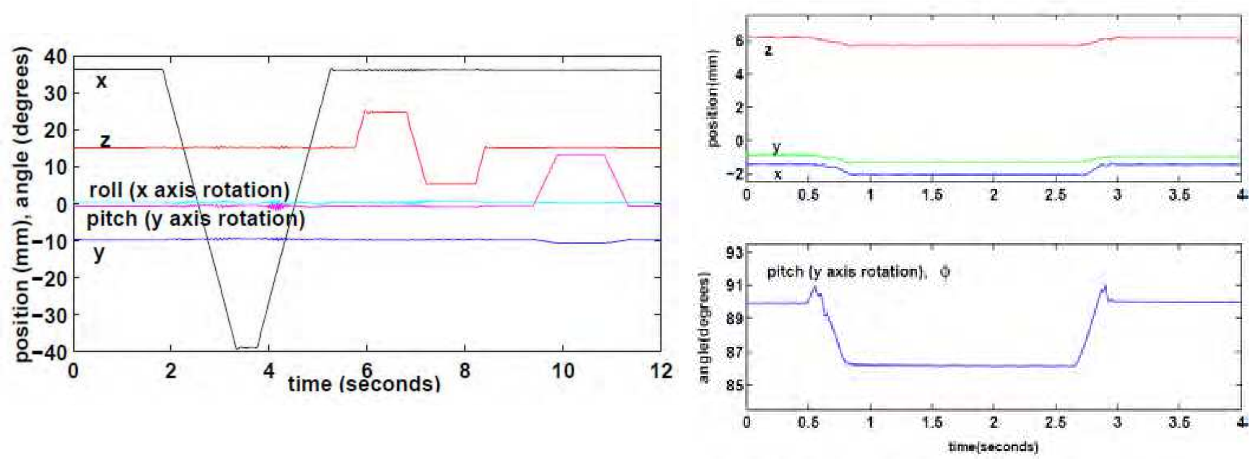

Fig. 11. (a) Motion trajectory for magnet in horizontal orientation, (b) vertical orientation

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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.