Interacting with Virtual Environments using a Magnetic Levitation Haptic Interface

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Abstract

A high-performance magnetic levitation haptic interface has been developed to enable the user to interact dynamically with simulated environments by holding a levitated structure and directly feeling its computed force and motion responses. The haptic device consists of a levitated body with six degrees of freedom and motion ranges of ± 5 mm and ± 3.5 degrees in all directions. The current device can support weights of up to 20 N and can generate a torque of 1.7 Nm. Control bandwidths of up to 50 Hz and stiffnesses from 0.01 to 23 N/mm have been achieved by the device using a digital velocity estimator and 1 KHz control on each axis. The response of the levitated device has been made successfully to emulate virtual devices such as gimbals and bearings as well as different dynamic interactions such as hard solid contacts, dry and viscous friction, and textured surfaces.

1 Introduction

In order for humans to interact more effectively with computers, the capability of humans to use various types of sensory data must be exploited. One means is by haptic perception of forces and torques on a user's hand while interacting with an artificial environment. Rendered graphics and virtual reality displays can generate realistic appearances of simulated environments, but do not enable the virtual world to be felt or manipulated directly. An ideal haptic interface would give a computer user the ability to feel, grab, and manipulate virtual objects. The dynamic reactions of objects in the simulated world would be instantly transmitted to the hand of the user as the motions or forces of the user's hand are sampled by the interface.

Tasks that have been integrated with some type of haptic interface include flight simulators, force-reflecting teleoperation and telepresence, and simulated molecular docking. Additional activities which could benefit from an effective haptic interface are CAD systems, assembly simulations, or any computer interface task which currently uses an input device such as a mouse, tablet, or joystick.

In our system, the user grasps a ball which exhibits a desired dynamic behavior [1]. As the user moves the ball, he or she directly feels the forces and torques generated by a realtime simulation of a physical system. The user can then use this tool to interact with the simulated environment application in a meaningful, intuitive way. The goal of our work is to provide the computer user with responsive and realistic interaction with complex 3-D simulated environments.

We have adapted a magnetically levitated positioning device, the *magic wrist* [2], into a high-performance haptic interface. This device has a single moving part levitated by forces between fixed magnetic fields and current-carrying coils in the levitated body. This structure and actuation eliminates the problems of friction and hysteresis inherent in articulated systems such as robotic arms and linkages. Furthermore, the levitation device provides a high degree of accuracy and a superior control bandwidth. The results obtained by Salcudean *et al* with a similar wrist at the University of British Columbia are reviewed and compared with those described here [3]. The following sections present a review of haptic interface research, the development of the magnetic levitation haptic interface, the mechanisms and interactions simulated with the interface, performance results, future development, and conclusions.

2 Haptic Display Background

Haptic interfaces and displays recently have received considerable research attention in the areas of human perception, physical simulation, and devices. There is not yet much effort, however, in unifying the control of the haptic interface and the physical simulations in order to provide realistic interaction between the user and a virtual environment.

Typically, manipulator arms are used as haptic devices, although other approaches include parallel linkage mechanisms and tensioned cable devices. Since the user physically interacts with the haptic device, the backdrivability, inertia, hysteresis, friction and other parameters of the dynamic behavior of the device are critical to its haptic performance.

Some research groups have developed kinematically parallel mechanisms with cables or linkages to avoid the problems of backdriven robot arms [4, 5]. Other groups have begun to focus on devices for operation by the hand and fingers such as a ten-DOF "sensor force" glove [6] and a bellows-actuated six-DOF pneumatic wrist [7]. A high-performance three-DOF fingertip haptic device which uses a parallelogram linkage and

cable transmission has been shown in interaction with simple virtual environments [8] and is commercially available. These small devices exhibit lower friction and higher control bandwidths than typical manipulators.

As various research devices have been created, researchers have begun to address more fundamental issues of haptic interaction with synthetic environments. In [9], 6-DOF input devices were used to interact with a synthetic 3-D environment and the authors concluded that the tasks considered would be very difficult with lower-dimensionality devices. Colgate *et al* studied factors affecting the achievable impedances for wall contact using a one-DOF device [10]. Performance tradeoffs and acceptable impedance bounds for free and constrained motion were established experimentally in [11]. Brooks's group observed that the manipulator arm haptic interfaces they were using were marginally adequate and noted that mechanical backlash, static friction, and other motion problems were "very troublesome"[12]. In their experience, a haptic device using finger and hand motions rather than arm motions would be preferable. Minsky *et al.* developed a software environment which displayed texture to the hand through a joystick rather than simple contact with rigid surfaces [13].

Examination of previous haptic interface studies leads to the conclusion that a small 6-DOF device with a high control bandwidth would be the optimal haptic interface. This ideal has led to the development of the magnetic levitation haptic interface described here.

3 Haptic Wrist

We are currently using a magnetically levitated fine-motion wrist shown in Fig.1 as a haptic interface [2, 14]. The wrist consists of a *flotor*, a a hexagonal box structure containing flat copper coils and position-sensing photodiodes, and a *stator*, a rigid support structure with mounted magnet assemblies and three narrow-beam LED's. To enable the user to manipulate the wrist easily, a ball grip was attached on top of the flotor. The flotor is stably levitated by driving controlled currents through the coils, producing Lorentz forces with the magnetic fields. The position and orientation of the flotor is calculated from the x, y positions of the LED spots on the photodiodes. Position and velocity feedback control in cartesian coordinates is used to control the dynamic impedance of the levitated flotor. A feedforward term cancels the weight of the flotor.

Digital state estimators were implemented to filter the sensed position data and provide smooth velocity data. Each control axis was assumed to be independent and was modelled as pure inertia from the dynamic response of the device. A more sophisticated estimator formulation was proposed in [15], in which external forces are estimated and corrected using the position errors.

The control system used for the magnetic levitation haptic interface consists of an Ironics IV-3204A 68020 single-board computer, a Mercury 3200 digital signal processor, and an i/o board with DAC and ADC daughterboards. The realtime control system is interfaced to a Sun3 host workstation with a Bit3 VMEbus adapter. Shared memory is used for communication with the host and block transfers are used to communicate with the DSP board.

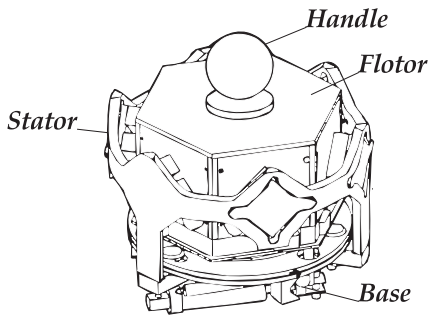

Figure 1: Schematic Representation of the Maglev Wrist

The host workstation handles user interface tasks through a graphical user interface. Data conversions, logging, and timing signals are done by the 68020 board in real time. Kinematics, dynamic simulations, coordinate transforms, and control are executed by the DSP board. This system has enabled control rates of over 1000 Hz using the Chimera multiprocessor operating system [16] developed at Carnegie Mellon University.

The distinguishing features of the magnetic levitation haptic interface are its high control bandwidth, simple open-loop dynamics, and motion in six degrees of freedom. The levitated haptic interface avoids the difficulties inherent in haptic interfaces using motors, linkages, and cables described earlier.

The open-loop dynamic response of the haptic device is essentially a single rigid-body inertia. The feedback gains determine the feel of the interaction and can be updated in real time to reflect changes in the simulated environment. Higher levels of control supply PD feedback gains, setpoints, and perform coordinate transforms between toolpoint and flotor frames. Appropriate selection and switching of these control parameters alone are sufficient to perform all of the haptic simulations described in the following section.

Due to the limited range of motion, rate control is necessary for access to a large manipulator or simulation space. For large-scale motion, the velocity of the end effector is set proportional to the position of the haptic interface. For close, detailed manipulation involving surface contacts, the control mode is switched back to force-reflecting position control. This approach was used in a coarse-fine teleoperation system with the UBC maglev wrist [17].

Although the range of motion of the levitated haptic interface is small compared to back-driven manipulators or linkages, the interface can be manipulated using the fingertips only while the user rests his or her wrist on the stator. No tiring extra movements are required, yet the dexterity and sensitivity of human fingers can be used to its full advantage. Since the device is small enough to fit on a desktop, it is con-

Figure 2: Using the Magnetic Levitation Haptic Interface with a Graphical Display

venient to use with a graphical display (Fig. 2) and presumably can be used for long periods of time with little or no fatigue on the part of the user.

4 Haptic Simulations

This section describes the types of dynamic behaviors that have been simulated with our haptic interface. The stiff wall and friction emulations implemented on the UBC maglev wrist and our wrist are compared. These simplified, *ad hoc* dynamic simulations demonstrate the potential performance of the interface if it were linked to a detailed, sophisticated realtime simulation of a virtual dynamic world.

By tuning the impedances of separate control axes, a number of simple mechanisms can be emulated. For example, high gains on all axes but one will emulate a linear or rotary bearing, depending on whether the free axis is translational or rotational. Likewise, if the x and y translation axes and the z rotation axis are made compliant, the haptic interface emulates a frictionless horizontal surface.

By applying matrix transformations to the control setpoints and feedback gains, an arbitrary center of compliance can be established for the haptic interface. The usefulness of remote center compliance in robot assembly tasks has is already well established, but remote center compliance is also useful for simulated environments. For example, a virtual hand-held tool has a center of compliance where the tip contacts a virtual solid object. Remote center compliance has been demonstrated successfully with our haptic interface.

To emulate contact with rigid surfaces, the control mode is switched between free motion and surface contact modes as the center of compliance in the flotor frame passes into or out of a virtual surface. This simple method resulted in a surprisingly realistic feel for the user. Rapid switching of the gains, setpoints, and coordinate frame gave the user a realistic illusion of actually colliding with a rigid surface with the gripped flotor. Since the forces on the flotor are calculated for collision with a real surface, the virtual collision even *sounds* like a real collision. Any problem of chattering during hard contacts can be eliminated by increasing the damping normal to the surface.

Stiff walls were simulated on the UBC wrist by switching gains and generating a braking impulse $f_{pulse} = -mv/T$ for one sample period to cancel the momentum of the flotor whenever the virtual toolpoint penetrates the virtual wall [3]. This method does not destabilize the system and was reported to produce convincing impacts with hard surfaces.

The contact modes and transitions involved in polyhedral contact are somewhat more complex than for single point contacts. For example, the possible contact modes between a convex polyhedron and a rigid surface are planar contact, line contact, and point contact. The conditions for each type of polygonal contact are 1) for free motion, no polygon vertices are in the surface 2) for point contact, only one vertex is in the surface 3) for edge contact, two vertices on an edge both penetrate the surface and 4) for planar contact, three vertices, or two vertices on different edges penetrate the surface.

To simulate polygonal contacts with a frictionless plane, the z axis is defined normal to the virtual surface. For point contact, the center of compliance is set to the point of contact and motion of that point into the surface is constrained. In edge contact, the x axis of the control frame is set to the edge of the polygon contacting the surface and rotation of that line into the plane is constrained. For plane contact, the contact area may translate or rotate in the plane, but translation or rotation into the plane is not allowed. The gains appropriate to each control axis for simulation of different contact modes are summarized in the following table with compliant axes indicated by dashes and stiff axes by X's.

contact mode	x	y	z	θ_x	θ_y	θ_z
free motion	-	-	-	-	-	-
point contact	-	-	X	-	-	-
line contact	-	-	X	X	-	-
planar contact	-	-	X	X	X	-

We are currently developing a haptic simulation of a disk on a frictionless surface with free motion, point contact, and planar contact modes. The damping in the vertical direction during surface contact results in the perception of adhesion as the virtual object is moved away from the surface, indicating that a more sophisticated transition model is needed.

We simulated contact with a textured surface by defining a rigid surface with sawtooth ridges 200 μm wide and deep. As the compliance point moves across the ridges, the user feels and hears some vibration due to the height variations in the surface. Parallel to the ridges, the user feels only frictionless motion on the surface. Although the difference between motion across the ridges and parallel to the ridges can easily be felt, a more detailed physical model of could provide a more realistic feel of surface texture.

Friction was simulated by shifting the control setpoints depending on the force applied by the user. Above a given force threshold, the position setpoints are adjusted proportionally in the appropriate direction. This simulates Coulomb friction and viscous

drag on the motion of an object, resulting in a convincing feel of planar contact with friction. Refinements under development are to implement separate static and dynamic friction and a coefficient of friction proportional to the normal force for planar contact. A similar model of stick-slip friction was implemented on the UBC maglev wrist [3]: Regular PD control is applied below the force threshold, while above the threshold only damping is used. When the external force drops below the threshold, the position setpoint is reset to the current position.

5 Results and Discussion

The performance of a haptic interface is difficult to measure directly, since it is determined by the user's subjective perception of the simulated environment. The dynamic behavior of the device itself as it emulates the modelled interactions can be measured instead to indicate the effectiveness of the haptic interface, however.

The limitations of the closed-loop dynamic behavior of the haptic interface result from the sampling rate, structural resonance frequencies, sensor noise, amplifier saturation and time constant, and heat dissipation in the actuator coils. The levitation device can lift a weight of 20 Newtons in addition to the 9.4 N weight of the flotor body. The maximum torque is 1.7 Newton-meters about the vertical axis. The maximum force and torque may not be sustained indefinitely since the unit overheats due to resistive dissipation in the flotor coils. During typical operation, the flotor becomes slightly warm to the touch.

The translational stiffness with zero feedback gains was measured as approximately 0.01 N/mm using a gram scale. This residual stiffness is due to the ribbon cables on the wrist and small variations in the actuator magnetic fields. The maximum stiffness and damping gains are limited by excitation of structural resonances. The maximum gains without exciting unmodelled resonances were found experimentally and are listed in the table below.

maximum gain	translation	rotation
position	23 N/mm	0.83 Nm/degree
velocity	0.165 Ns/mm	0.0047 Nms/degree

An analysis of the UBC wrist controller produced stability limits on gains due to the discretization in the controller implementation [3]. This consideration poses less of a problem in our implementation due to a 1 KHz sample rate instead of 200 Hz and because the velocity and position data predicted by the estimator reduce the effects of computation delays.

Figure 3 shows the closed-loop position response of the vertical axis of the haptic device with high stiffness and damping as measured with a Hewlett-Packard 3562A dynamic signal analyzer. The response magnitude lies within a ± 3 dB range around the DC gain up to approximately 50 Hz. It is speculated that the notches in the response magnitude at 30 and 50 Hz and are due to resonances in the ribbon cables from the stator to the flotor.

Tuning the digital estimator gains involves a tradeoff between output smoothness and the disturbance

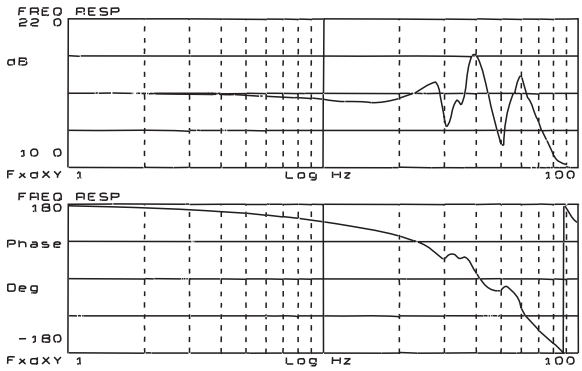

Figure 3: Positional Control Frequency Response

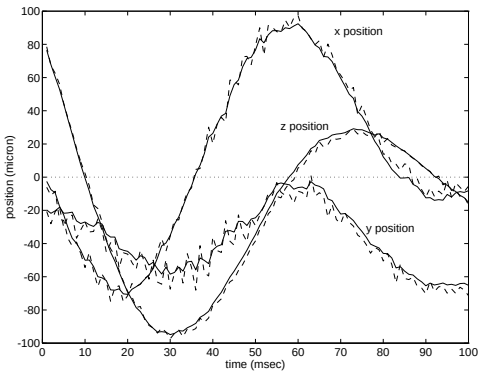

Figure 4: Position Data from Sensors (dashed lines) and Estimator (solid lines)

response. Since disturbances result mainly from the motions and forces of the user's hand and have limited bandwidth, the estimator gains were chosen to filter frequencies above approximately 25 Hz. The plant model used only the flotor inertia; damping from eddy currents and the user's hand were regarded as disturbances. Position data and estimator outputs with a sinusoidal disturbance are shown in Fig.4.

The measured relationship of force to planar position for a simulated square box is shown in Fig.5. To obtain this figure, the wrist flotor was manipulated by hand for 20 seconds inside a planar 1 mm square virtual box. The magnitude of the reaction forces as the virtual toolpoint contacts the virtual walls is shown on the vertical axis. Figure 6 shows the recorded position and force during a collision with a stiff virtual surface. The fast oscillations in the response are likely due to structural resonances while the slower oscillations are due to the impedance of the closed-loop control and the user's hand. This vibration feels natural to the user for hard impacts.

6 Future Work

Further development will concentrate on redesign and fabrication of a new levitation device and development of more sophisticated dynamic simulation models. Planned improvements for a new magnetic

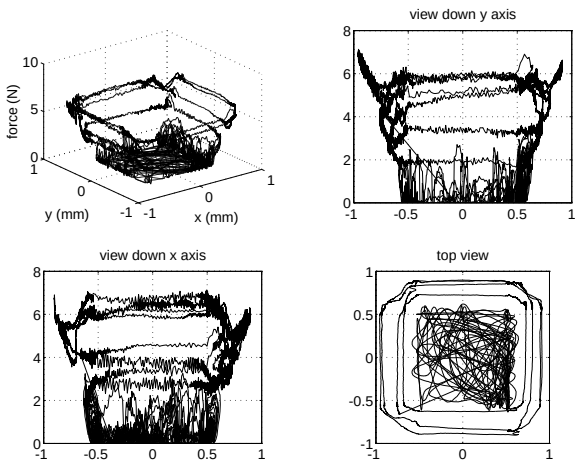

Figure 5: Virtual 2-D box with Force Magnitudes

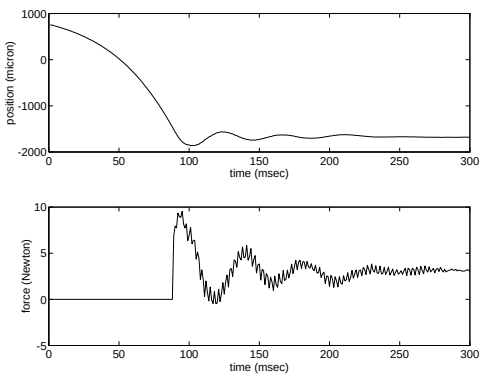

Figure 6: Collision With a Virtual Wall

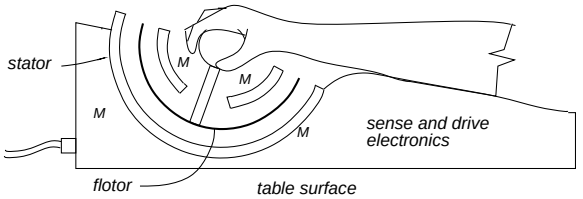

Figure 7: Proposed Spherical Design

levitation haptic interface include a greater range of motion, simplified lightweight design, more powerful actuators, reduced structural vibration, and a shape to fit the user's hand. Advanced simulation methods would then enable even more natural interaction with complex environments.

The hexagonal arrangement of the Lorentz actuators in the present haptic interface results in an irregular range of motion in translation and rotation. The full range of rotation is only achieved when the flotor is in the center position and full translation is only possible when there is no rotation. A hemispherical flotor is proposed as a solution to the irregular motion ranges of the present haptic interface. A rounded flotor shell would result in decoupled translation and rotational motion since there would be no corners on the flotor to collide with the stator during rotation, and the round open shape allows the user to reach comfortably inside the flotor shell to grasp a tool at its center and make the best use of the rotational capabilities of the device. A more compact and efficient configuration for the six magnetic actuators assemblies has also been found for a hemispherical geometry.

The spherical shape would result in a stiffer lightweight flotor with fewer parts than the present wrist. Further reduction in weight can be achieved by fixing the position sensors on the stator and moving the three LED's to the flotor. This new configuration introduces added difficulty in design and fabrication, however, since the magnets, coils, sensors, and support frame must all conform to the spherical shape. An example of the hemispherical geometry is pictured in Fig.7.

A motion range of 25 mm in translation in all directions is planned for the new haptic device to correspond to the natural range of motion for a typical user's fingertips. The radius of the flotor should be approximately 100 mm to minimize the floated mass yet allow the user to grip a handle at the center of the flotor.

The environments and dynamic interactions that we have emulated with our haptic interface so far have involved only single contacts and objects. These methods will be insufficient for simulated environments which may contain many more objects and surfaces. A general method is needed to detect and model contact with multiple objects of arbitrary shape in real time. A graphic display of the simulated environment during operation of the haptic interface would also provide more useful and realistic user interaction. Interactive graphical simulations with virtual environments in 3-

D involving rigid and non-rigid body dynamics, collisions, and frictional contact have been developed by Baraff *et al* [18, 19]. Their methods utilize a physical treatment of the subject which has been shown to be both more practical and correct than the *ad hoc* spring-and-damper treatments used in other systems that handle contact. We aim to merge our haptic interface with an interactive graphic simulation system such as Baraff's, enabling the user to feel force interactions through the levitated hand grip as it moves while seeing the 3-D modelled environment graphically rendered in real time. Such an integrated system could then simulate user tasks such as tool manipulation and assembly in a realistic complex environment.

7 Conclusion

We have demonstrated that a magnetic levitation device under high-speed control can effectively function as a haptic interface to enable a user to interact physically with simulated dynamic environments. Rigid body interactions such as impact, sliding contact, texture and static friction have been emulated. Because of the fast sample rate and efforts taken to achieve near-optimal sensing and control accuracy with the available hardware, realistic haptic interaction resulted from simple control methods and dynamic models. The results obtained were consistent with those observed on the UBC wrist [3]. Judging from the results obtained with the present device and simple simulations so far, we expect improvements in levitation device and simulation to result in further improved performance. A haptic interface shaped to easily fit the hand and capable of a larger motion range, coupled with a sophisticated realtime dynamic simulation and a graphic display, will enable natural user interaction with more complex and realistic virtual environments.

Acknowledgements

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