Interactive Dynamic Simulations with Co-Located Maglev Haptic and 3D Graphic Display

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***Abstract*—We have developed an system which combines realtime dynamic simulations, 3D display, and magnetic levitation to provide high-fidelity co-located haptic and graphic interaction. Haptic interaction is generated by a horizontal array of cylindrical coils which act in combination to produce arbitrary forces and torques in any direction on magnets fixed to an instrument handle held by the user, according to the position and orientation sensed by a motion tracking sensor and the dynamics of a realtime physical simulation. Co-located graphics are provided by a thin flat screen placed directly above the coil array so that the 3D display of virtual objects shares the same volume as the motion range of the handheld instrument. Shuttered glasses and a head tracking system are used to preserve the alignment of the displayed environment and the interaction handle according to the user's head position. Interactive demonstration environments include rigid bodies with solid contacts, suspended mass-spring-damper assemblies, and deformable surfaces.**

***Keywords*-haptics, interaction, simulation**

I. Introduction

The ideal of virtual reality and haptic interfaces is to physically interact with simulated objects with the highest possible fidelity in both the graphical display and the kinesthetic forces and torques sensed by the user during interaction. Computer-generated graphics can produce highly realistic, dynamic 3D imagery in real time, but haptic interfaces are generally based on single point contact feedback, tactile cues, and linkage devices which have various limitations in their force and motion ranges, frequency response bandwidth, and resolution.

Our system combines a graphical display with a large range of motion magnetic levitation device, as shown in Fig. 1. The graphical display is placed directly above a horizontal array of cylindrical coils and underneath the instrument handle held by the user, so that electromagnetic forces and torques can be generated on magnets embedded in the handle as the instrument is moved by the user into contact with the displayed simulated environment.

The magnets in the instrument handle, the coil array with its current amplifiers, and the motion tracking sensor with its infrared LED markers, function together as a magnetic levitation system. Its motion range is approximately 100x100 mm horizontally, up to 75 mm vertically, with unlimited yaw and tilt up to 40 degrees.

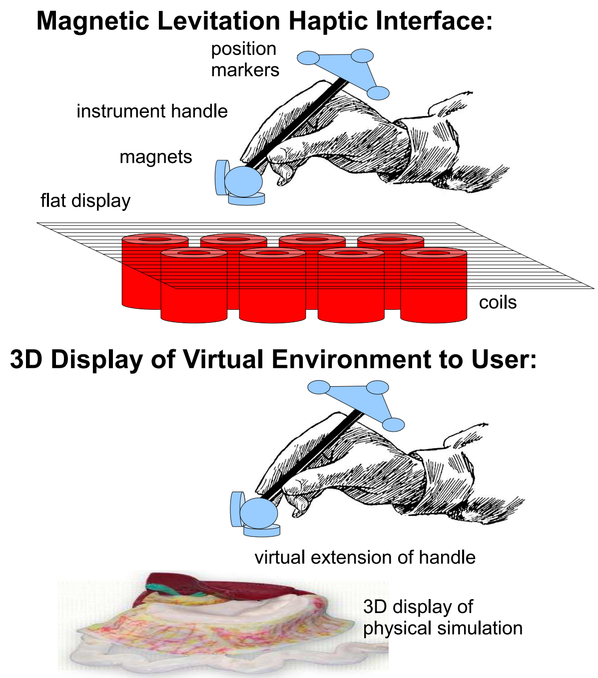

Figure 1. Co-Located Maglev Haptic and 3D Graphic Display

A secondary, slower and less precise motion tracking system tracks the position of the user's head so that the 3D views are generated correctly according to the position of each of the user's eyes. A pair of shuttered glasses, synchronized to the update rate of the graphics on the monitor, is worn by the user so that each eye sees a different image as the shutters alternate. In practice, this head tracking system allows the user to observe the handheld instrument and the 3D displayed environment together from the side and from above, in a natural ergonomic position for hand-eye coordination during dextrous manipulation of a handheld instrument or tool. Examples of relevant dextrous

 ISBN: 978-1-61208-250-9

tool manipulation tasks include any writing, carving, or cutting tasks, operation of wrenches or screwdrivers, and medical needle manipulation for suturing, injections, and biopsy.

The real-time haptic interaction and graphical display are generated from a dynamic simulation which must perform collision detection, finite element deformation, and haptic rendering sufficiently quickly to support graphical updates at 30-60 Hz and haptic interaction and magnetic levitation at 800-1000 Hz. These tasks are sufficiently computationally intensive to be the limiting factor regarding the resolution and realism of the simulated environment.

II. Background

The realization of our interactive system depends on the performance and integration of technology in the areas of maglev haptics, graphics, and physical simulation. Relevant prior work in each of these areas is surveyed below.

A. Co-Located Haptics and Graphics

3D graphics and haptic force and/or torque feedback can be generated at the same location by simply placing the 3D display behind the haptic interaction device, however this method has two drawbacks. First, the body of the haptic interface device partially occludes the display, and second, there may be a significant difference produced between the perceived location of the displayed imagery and the surface of the screen, so that the convergence and focal distance of the user's eyes do not match, which is unnatural and may cause discomfort to the user.

ReachIn, *Immersivetouch*, and *SenseGraphics* systems [1] use a partially silvered mirror between the head and hand of the user, so that the display can be moved out of the way and the focal and convergence distances of the user's eyes can be matched. The haptic device and the user's hand do not occlude the 3D graphics behind them, but rather the real and virtual environments are superimposed and semitransparent due to the half-silvered mirror, which may be a distraction to the user.

The "what you see is what you feel" system [2] uses a thin flat display with a camera behind it. The video image of the user's hand is then extracted from the camera view using a green screen chroma-key technique, and rendered in the virtual environment. Holographic display [3] is another method which has been used for haptic and graphic co-location.

Comparative studies have shown [4], [5] evidence of improved perception and performance from co-located haptic interaction.

B. Haptic Magnetic Levitation

Hollis and Salcudean first applied Lorentz force magnetic levitation devices [6] to haptic interaction and force-feedback teleoperation. Lorentz force magnetic levitation haptic interaction development continued with other more specialized device designs [7] [8] and larger range devices developed by Berkelman [9] [10].

The design and function of the magnetic levitation system used here is described in [11]. This system uses a fixed planar array of cylindrical coils to levitate a platform of one or more cylindrical magnets. The yaw of the levitated platform is unlimited and its horizontal motion range is determined by the size of the planar array. Vertical levitation distances of up to 75 mm and tilt angles of 45 degrees are achievable, depending on the mass of the levitated platform and the dimensions of the magnets used.

Similar tabletop-scale large range magnetic levitation systems have been developed for suspension of models in wind tunnels [12] and for micromanipulation using pole pieces to shape magnetic fields [13].

C. Realtime Physical Simulation

Realistic software simulations of dynamic physical environments have been developed by Baraff both for rigid [14] and deformable [15] objects, including efficient collision and reaction force detection and surface friction. Freely available physical simulation software packages include the SOFA framework [16] [17], Bullet Physics, and the PhysX library from NVIDIA. Higher resolution and performance can be obtained by using precomputed deformation modes [18] and 6-DOF haptic rendering including torque feedback as well as force on an interactive instrument can be integrated with simulations [19].

Several software packages are freely available for haptic rendering and realtime physical simulation. H3D [20] and Chai3D [21] include driver interfaces for common commercial haptic interface devices such as the Sensable Technologies Phantom [22]. A programming interface is also available with the magnetic levitation haptic interface from Butterfly Haptics LLC [23].

III. Implemented System

The motion tracking, magnetic levitation control, haptic rendering, physical simulation, and graphical display in our current system are all executed in real time in separate threads on a single quad-core PC in Linux 2.6. GNU C/C++ was used for all programming. An initial demonstration concept of the system with a simulation of a single paddle instrument and a ball rolling on a plane, an earlier magnet and coil configuration, and a conventional 2D display was demonstrated previously [24]. The current system is shown in Fig. 2, including the planar 3D display, haptic instrument handle, current amplifiers, and head tracker.

A. Magnetic Levitation

The motion tracking of the handheld instrument in our system is done using a Northern Digital Optotrak Certus position sensor and three infrared Smart Markers. Motion

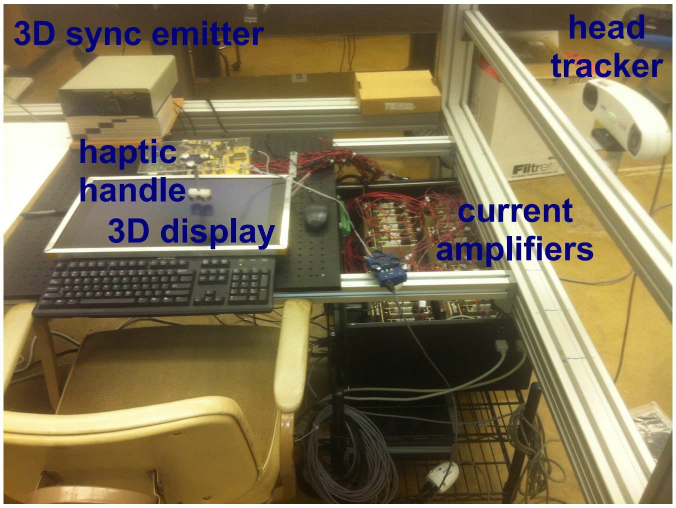

Figure 2. Implemented system

tracking updates are provided at 860 Hz with a position resolution of approximately 0.01 mm for each marker. Actuation forces and torques are generated by a closely packed array of 27 cylindrical coils, each with 1000 windings, 25 mm diameter, and 30 mm height. Either a two-magnet or four-magnet instrument handle can be used with the system; the two-magnet 125 g instrument can provide greater haptic forces and torques but is more massive and bulky, and the smaller 75 g four-magnet instrument occludes the user's view of the display less due to its compact size. Forces are limited to approximately 4 N due to heating of the actuation coils, although higher momentary peak forces are possible.

The four-magnet instrument is shown in Fig. 3 levitated above the 27-coil array at a height of 30 mm and a tilt angle of 20 degrees. This coil array is underneath the 3D display monitor shown in Fig. 2. The motion tracker for the haptic instrument is mounted on a rigid frame at ceiling level, looking downwards.

The design and evaluation methods used in the development of the magnetic levitation system are described in [25].

B. 3D Display

The NVIDIA 3D Vision package was used with Linux drivers to provide 3D display of the simulated environment. This package uses shutter glasses which are synchronized with the graphics card by an infrared emitter box. A Quadro 4000 graphics card was used with a ViewSonic vm2268 monitor with a 120 Hz update rate. OpenGL and GLUT graphics libraries are used for the 3D graphics rendering.

The case of the monitor was removed and backplane circuit boards and wiring were moved so that the monitor backlight and display could be placed directly on the coil array. The combined thickness is under 10 mm, so that haptic forces and torques can be applied to the handheld instrument up to a vertical height of at least 60 mm. Magnetic fields

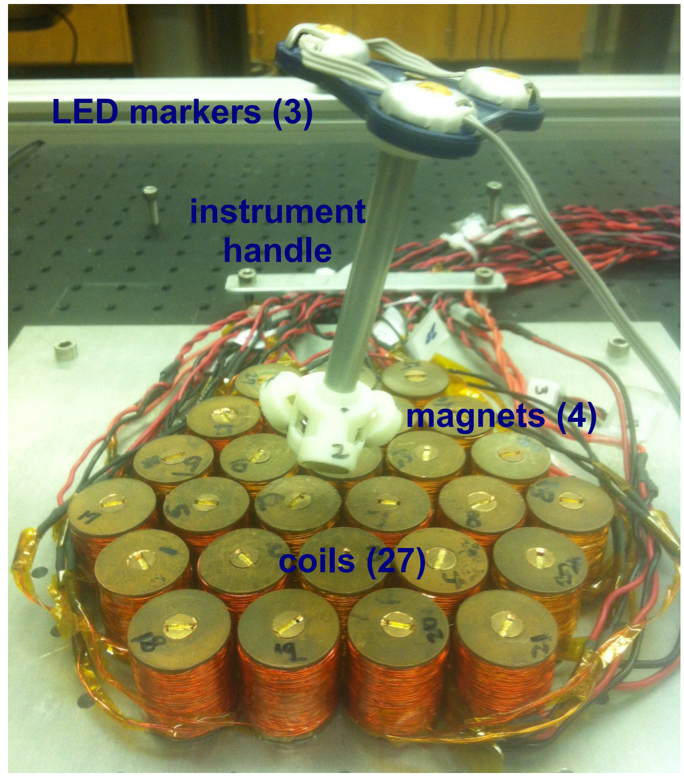

Figure 3. Levitated 4-magnet instrument

from the instrument magnets and coil array were not found to interfere with the display, and there are no ferromagnetic components in the display to interfere with the magnetic levitation system. A thin sheet of plastic was placed on the monitor screen for protection from impacts from the magnets and instrument.

Head tracking was implemented using a Northern Digital Polaris Vicra and passive reflective markers to produce correct 3D display according to the position of each eye. The spatial position and orientation of the shutter glasses from the positions of four reflective markers fixed to the glasses. Position and orientation data were updated at a 10 Hz rate with a resolution of approximately 0.1 mm for each marker. It would be possible to track both the magnet instrument and and the user's head using a single motion tracking system, but this would require using wired infrared markers on the 3D shutter glasses, slowing down the update rate of the magnetic levitation localization due to the additional LED markers on the glasses, and mounting the localizer at least 3.5 m high so that its sensing volume includes the location of the glasses.

As both the Optotrak and Polaris motion trackers use infrared position sensing, and 3D Vision systems uses infrared communication to synchronize display frames with the shutter glasses, it is necessary to ensure that each infrared system does not interfere with the others. In our

 ISBN: 978-1-61208-250-9

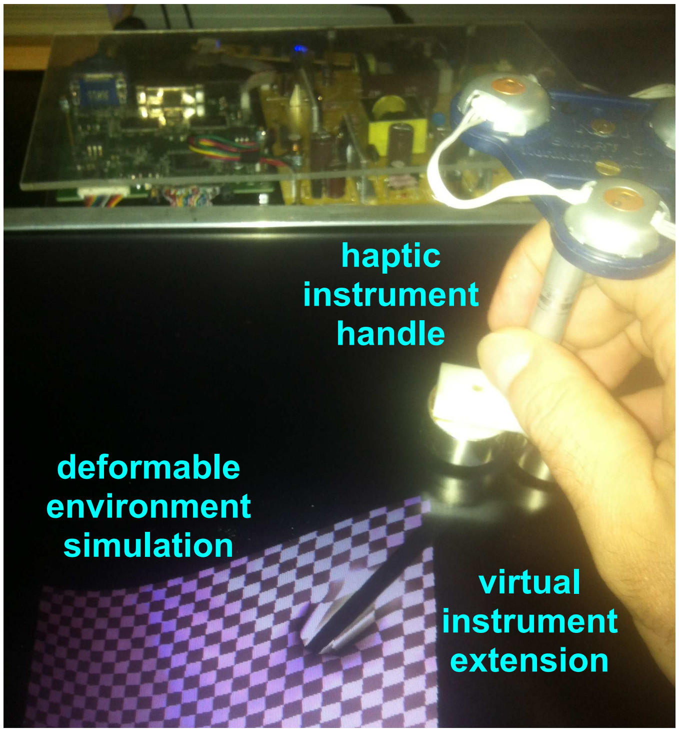

Figure 4. Deformable simulation

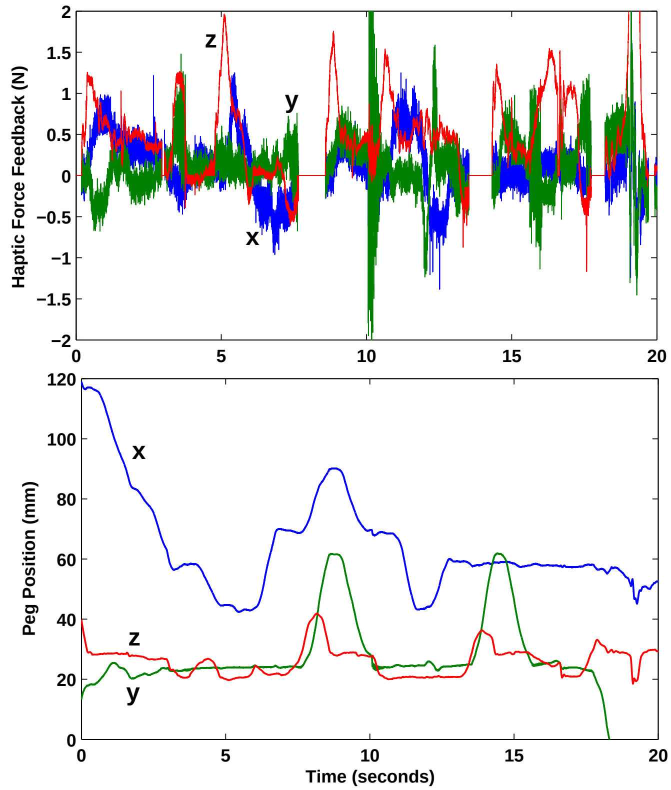

Figure 5. Interactive peg-in-hole simulation

system, each set of emitters and receivers are oriented in orthogonal directions and positioned so that each emitter is only visible to its corresponding receiver. The Optotrak sensor is mounted above the table looking down at the LEDs on the instrument, the Polaris is mounted on the side of the table to track the reflective markers on the side of the glasses, and the synchronization emitter is mounted at the front of the tabletop.

C. Simulations

Basic interactive simulations which have been implemented on our system at present include point, edge, and face contacts between simple solid shapes such as square peg-in-hole insertion, simple dynamic environments including suspended masses and springs, and rolling objects. These simple initial simulations allow the dynamics and contact models of the environments to be modified and adjusted to provide the most realistic haptic interaction while preventing unstable dynamics.

A more sophisticated simulation which involves an instrument contacting a deformable surface is shown in Fig. 4. In this simulation, a virtual extension is added to the actual haptic instrument handle, and the deformation of the surface and reaction forces and torques on the instrument are calculated at the haptic update rate. Damping is added to the internal dynamics of the deformable body and the surface dynamics during contact with the haptic instrument.

The MLHI library and programming interface, originally from Butterfly Haptics, has been adapted for use with our system, and can be used for haptic rendering and communication between simulation and magnetic levitation threads with a haptic update rate of 1000 Hz. Alternatively, haptic rendering and dynamic simulation calculations can be performed synchronously with the motion tracking at 860 Hz.

IV. Results

Force and position experimental data in x, y, and z directions obtained during interactive simulations are presented in Figs. 5 and 6. The position data was measured by the position tracking system, and the force data are calculated by the simulations and generated by the coil array of the magnetic levitation system in real time. The commanded forces were shown to be within 0.1 Newtons of force sensor measurements throughout the range of the magnetic levitation system in [11].

The Fig. 5 plots are from a haptic peg-in-hole simulation in which a 25 mm square peg is controlled by the haptic instrument handle and inserted into a 27x54 mm, 10 mm deep square hole. The Fig. 6 plots are from a deformable simulation in which a pointed virtual instrument contacts a deformable object, as shown in Fig. 4. For both cases, haptic forces and torques are zero while the instrument is moving freely, contact forces are approximately proportional to the

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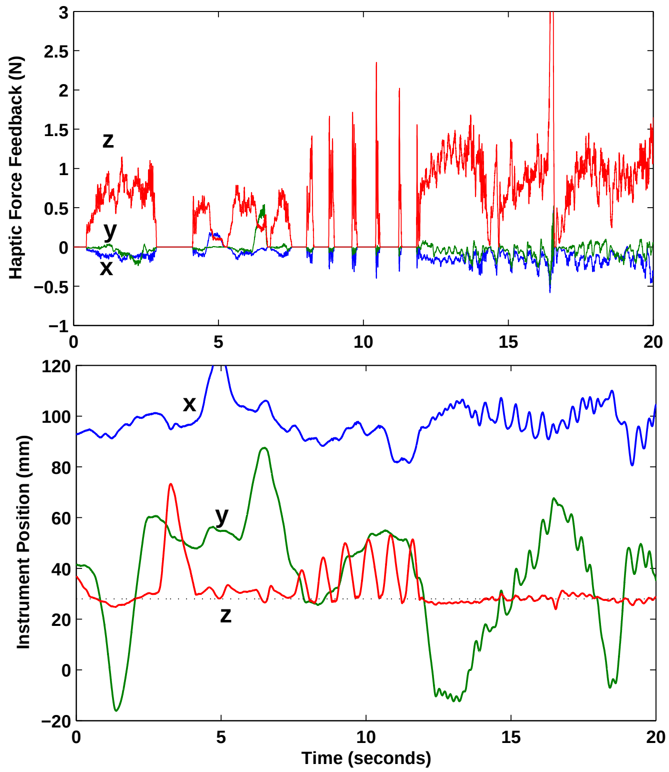

Figure 6. Interactive palpation of deformable surface

depth of contact, and haptic torques depend on each contact force and the displacement between the contact point and the center of the haptic instrument and simulated tool.

In the peg-in-hole simulation of Fig. 5, the peg is not in contact with the hole or top surfaces at the 8-9 and 14-15 second intervals, the z coordinate is greater than 30, and there is no haptic force feedback. As the peg is moved in and out of the hole, the z position moves between 20 and 30 mm. The x position can vary between approximately 40 and 70 mm while the peg is in the hole, as the hole is more than twice as wide as the peg in the x direction. Non-zero x and y forces are present when the virtual peg is pushed against any of the four sides of the virtual hole. Contact stiffnesses are approximately 0.4 N/mm and the kinetic and static friction coefficents are 0.15 in the simulations.

For the deformable surface of Fig. 6, the probe is moved across the surface during the 12-20 second interval, and the surface is struck with the probe several times from 8-12 seconds. The object was modeled with millimeter-scale surface variations rather than a smooth flat surface. This surface texture therefore produces variable vertical (z) forces in response to horizontal (x and y) motions of the intstrument tip. Oscillations in both the position and force data can be seen in the 12-20 second period due to sticking and slipping of the sliding surface contact. Overall the force plots are smoother in the deformable surface simulation than the peg-in-hole simulation due to the compliance and lower friction of the deformable surface.

V. Further Work

At present, the magnetic levitation and motion tracking aspects of our system are fully developed, but the interactive environments are at a preliminary stage. We plan to refine the detail and physical realism of the simulated environments to a degree where they are useable and provide measureable benefits in medical training tasks such as surgery, intubation, and needle driving. User studies will be conducted to evaluate the benefits of colocated haptic and graphical training of simulated medical procedures.

The complexity of the modelled environment and the sophistication of the simulated dynamics can be improved by using the graphics processor for additional numerical computations, as a general purpose graphics processing unit or GPGPU. NVIDIA provides the CUDA [26] programming interface to utilize the parallel processing capabilities of the GPGPU on the graphics cards used.

One more planned improvement to be made on the system is to reconfigure the system to be simpler and more compact.

VI. Conclusion

Our co-located haptic and graphic interface system is novel in that there is no hardware between the user and the display other than the handheld interaction instrument. The 3D environment is displayed close to the surface of the monitor, so there is no conflict between visual convergence and focal ranges. Electromagnetic force and torque actuation is used for haptic interaction rather than a motorized linkage, providing advantages in backdriveability, precision, and response frequency bandwidths.

We have demonstrated the feasibility and function of our system with the basic simulation environments described.

Acknowledgment

This work was supported in part by National Science Foundation grants IIS-0846172 and CNS-0551515, and by the University of Hawaii College of Engineering.

References

[1] C. Luciano, P. Bannerjee, L. Florea, and G. Dawe, “Design of the ImmersiveTouch: a high-performance haptic augmented virtual reality system,” in *11th International Conference on Human-Computer Interaction*, Las Vegas, August 2005.

[2] Y. Yokokoji, R. Hollis, and T. Kanade, “WYSIWYF display: A visual/haptic interface to virtual environment,” *Presence*, vol. 8, no. 4, pp. 412–434, August 1999.

[3] P. Olsson, F. Nysjo, S. Siepel, and I. Carlbom, “Physically co-located haptic interaction with 3d displays,” in *IEEE Haptics Symposium*, Vancouver, March 2012, pp. 267–272.

[4] D. Swapp, V. Pawar, and C. Loscos, “Interaction with haptic feedback and co-location in virtual reality,” *Presence*, vol. 10, no. 1, pp. 24–30, April 2006.

[5] G. Jansson and M. Ostrom, “The effects of co-location of visual and haptic space on judgements of form,” in *Euro-Haptics*, Munich, June 2004, pp. 516–519.

[6] R. L. Hollis and S. E. Salcudean, “Lorentz levitation technology: a new approach to fine motion robotics, teleoperation, haptic interfaces, and vibration isolation,” in *Proc. 6th Int'l Symposium on Robotics Research*, Hidden Valley, PA, October 1993.

[7] S. Salcudean and T. Vlaar, “On the emulation of stiff walls and static friction with a magnetically levitated input-output device,” in *ASME IMECE*, Chicago, November 1994, pp. 303–309.

[8] P. J. Berkelman, R. L. Hollis, and S. E. Salcudean, “Interacting with virtual environments using a magnetic levitation haptic interface,” in *Int'l Conf. on Intelligent Robots and Systems*, Pittsburgh, August 1995.

[9] P. J. Berkelman and R. L. Hollis, “Lorentz magnetic levitation for haptic interaction: Device design, function, and integration with simulated environments,” *International Journal of Robotics Research*, vol. 9, no. 7, pp. 644–667, 2000.

[10] P. Berkelman and M. Dzadovsky, “Extending the motion ranges of magnetic levitation for haptic interaction,” in *Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Salt Lake City, March 2009, pp. 517–522.

[11] ——, “Magnetic levitation over large translation and rotation ranges in all directions,” *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 1, pp. 44–52, 2013.

[12] N. J. Groom and C. P. Britcher, “A description of a laboratory model magnetic suspension testfixture with large angular capability,” in *IEEE Conference on Control Applications*, Dayton, September 1992, pp. 454–459.

[13] M. B. Khamesee and E. Shameli, “Regulation technique for a large gap magnetic field for 3d non-contact manipulation,” *Mechatronics*, vol. 15, pp. 1073–1087, 2005.

[14] D. Baraff, “Interactive simulation of solid rigid bodies,” *IEEE Computer Graphics and Applications*, vol. 15, pp. 63–75, 1995.

[15] D. Baraff and A. Witkin, “Dynamic simulation of non-penetrating flexible bodies,” in *Computer Graphics* (*Proc. SIGGRAPH*), vol. 26. ACM, July 1992, pp. 303–308.

[16] J. Allard, S. Cotin, F. Faure, P.-J. Bensoussan, F. Poyer, C. Duriez, H. Delingette, and L. Grisoni, “Sofa an open source framework for medical simulation,” in *Medicine Meets Virtual Reality (MMVR'15)*, Long Beach, USA, February 2007.

[17] M. Marchal, J. Allard, C. Duriez, and S. Cotin, “Towards a framework for assessing deformable models in medical simulation,” in *International Symposium on Computational Models for Biomedical Simulation*, London, July 2008.

[18] J. Barbic and D. James, “Six-dof haptic rendering of contact between geometrically complex reduced deformable models,” *IEEE Transactions on Haptics, preprint published online*, June 2008.

[19] D. James and D. Pai, “A unified treatment of elastostatic and rigid contact simulation for real time haptics,” *Haptics-e*, vol. 2, no. 1, 2001.

[20] *HAPI Manual*, 1st ed., SenseGraphics Inc., May 2009.

[21] Http://www.chai3d.org/.

[22] T. Massie and K. Salisbury, “The PHANToM haptic interface: A device for probing virtual objects,” in *Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Chicago, Illinois, November 1994.

[23] *Magnetic Levitation Haptic Interface API Reference Manual*, 1st ed., Microdynamic Systems Lab, Carnegie Mellon University, September 2008.

[24] P. Berkelman, M. Miyasaka, and J. Anderson, “Co-located 3d graphic and haptic display using electromagnetic levitation,” in *IEEE Haptics Symposium*, Vancouver, March 2012, pp. 77–81.

[25] P. Berkelman and M. Dzadovsky, “Novel design, characterization, and control method for large motion range magnetic levitation,” *IEEE Magnetics Letters*, vol. 1, January 2010.

[26] *Nvidia CUDA Compute Unified Device Architecture Programming Guide 1.0*, Nvidia, 2007.

 ISBN: 978-1-61208-250-9