Tool-Based Haptic Interaction with Dynamic Physical Simulations using Lorentz Magnetic Levitation

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Outline:

**Introduction:** haptic interaction background, devices

**Part I: Hardware**
- Lorentz magnetic levitation
- New design
- Actuation and sensing subsystems
- Performance testing

**Part II: Software**
- System integration
- Dynamic simulation
- Surface friction and texture
- Virtual coupling
- Intermediate representation

**Conclusion:** Summary, contributions, further directions
Haptic Interaction:

Challenge to physically interact with virtual objects as real:
• Technology limitations
• Different approaches:
  – Glove
  – Single fingertip
  – Rigid tool

For realistic haptic interaction:
• Device must be able to reproduce dynamics of tool and environment to match hand sensing capabilities
• Simulation must be able to calculate required dynamics and be integrated with device controller

Applications: CAD, medical simulations, biomolecular, entertainment
Haptics Background:

Definition of Terms:
- **Haptic Interaction**: active tactile and kinesthetic sensing with the hand
- **Haptic interface device**: enables user to physically interact with remote or simulated environment using motion and feel
- **Tool-based haptic interaction**: user interacts through a rigid tool

Prior Work:
- **Lorentz magnetic levitation**: Hollis & Salcudean [*Trs. R&A* 91, *ISRR* 93]
- **Surveys of haptic research**: Burdea [*Force and Touch Feedback*, 1996], Shimoga [*VRAIS* 93], Durlach & Mavos [*Virtual Reality: Sci. and Tech. Challenges*, Ch. 4, 1995]
- **Haptic perception**: study by Cholewiak & Collins [*Psych. of Touch*, 91]
- **Virtual coupling**: Colgate [*IROS* 95], Adams & Hannaford [*ICRA* 98]
- **Intermediate representation**: Adachi [*VRAIS* 95], Mark [*SIGGRAPH* 96]
New Maglev Haptic Device:

• New Lorentz maglev device developed specifically for haptic interaction
• User grasps and manipulates handle in bowl set in cabinet top
Other Haptic Interface Devices:

- Early exoskeletons and manipulators used for teleoperation and haptic interaction
- Recent devices use lightweight linkages and cables
- Specialized devices for medical procedures
- Fast response with 6 DOF is difficult
Lorentz Magnetic Levitation:

Force from current in magnetic field:

\[ f = - i \oint B \times dl \]

- Position sensing with LEDs and position sensing photodiodes
- 6 actuators needed for levitation

**Advantages:**
- Force independent of position
- Noncontact actuation & sensing, only light cable connection
- 6 DOF with one moving part

**Disadvantages:**
- Limited motion range
- Expensive materials and sensors
**Other Maglev Devices:**

IBM and UBC wrists:
- Developed as fine motion positioners carried by robot arm
- Used for haptic interaction with simulated surfaces, texture, and friction

|----------------------|-----------------|----------------------|

**IBM and UBC wrists:**
- Developed as fine motion positioners carried by robot arm
- Used for haptic interaction with simulated surfaces, texture, and friction

<table>
<thead>
<tr>
<th>Position bandwidths:</th>
<th>~50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position resolution:</td>
<td>1-2 μm</td>
</tr>
<tr>
<td>Motion range:</td>
<td>&lt;10 mm, &lt;10° motion ranges</td>
</tr>
</tbody>
</table>

UBC Powermouse recently developed, small cost and motion range
Design Goals for New Haptic Device:

- At least 25 mm translation range in all directions with as much rotation as possible
- Decoupled rotation and translation ranges
- >100 Hz position control bandwidth
- Micrometer level position resolution
- Low levitated mass
- Handle grasped at center of device rotation
New Device Design:

- Stator bowls enclose flotor hemisphere
- Curvature decouples rotation and translation ranges
- Device embedded in cabinet desktop
- User rests wrist on top rim to manipulate handle with fingertips
Actuator Coil Configuration:

- 115 mm radius fits magnet assemblies, user hand, motion range
- Coil configuration maximizes motion range and force/inertia ratio
- Efficient force and torque in all directions

To convert coil currents to force and torque on flotor:

\[ F = AI, \quad F = \{f_x, f_y, f_z, \tau_x, \tau_y, \tau_z\}, \quad I = \{i1, i2, i3, i4, i5, i6\}^T \]

\[ A = \begin{bmatrix}
-S(-\pi/8) & -S(\pi/3) & -S(2\pi/3)S(-\pi/8) & 0 & -S(4\pi/3)S(-\pi/8) & -S(5\pi/3) \\
0 & C(\pi/3) & -S(2\pi/3)S(-\pi/8) & -1 & -S(4\pi/3)S(-\pi/8) & C(5\pi/3) \\
C(-\pi/8) & 0 & C(-\pi/8) & 0 & C(-\pi/8) & 0 \\
0 & -C(\pi/3)S(-\pi/4) & S(2\pi/3) & S(\pi/4) & -S(4\pi/3) & -C(5\pi/3)S(-\pi/4) \\
-1 & -S(\pi/3)S(-\pi/4) & C(2\pi/3) & 0 & C(4\pi/3) & -S(5\pi/3)S(-\pi/4) \\
0 & -S(\pi/4) & 0 & -S(\pi/4) & 0 & -S(-\pi/4)
\end{bmatrix} \]
Single Lorentz Actuator:

- Tapered magnet assemblies and curved coils conform to hemispherical device shape
- Oversized coils in 30 mm magnet gap throughout motion range
Actuator Design FEA:

3-D finite element analysis model necessary due to geometry, air gaps, field saturation

- Larger magnets not necessarily better

20 mm magnets: 7.58 N/A force

25 mm magnets: 7.98 N/A force

30 mm magnets: 7.60 N/A force

30 and 45 mm magnets: 7.58 N/A force
Prototype Actuator Testing:

Magnetic field in center plane between magnet faces:

![Diagram showing magnetic field lines]

**FEA model**

**Measured Prototype**

Test actuator allows motion in one direction:

- 7.2 N/A measured force within 10% of FEA prediction
- Probably from differences in coil and magnet parameters
Position Sensing Geometry:

- Fixed lenses image light from LEDs on moving flotor onto fixed planar position sensing photodiodes
- Sensors provide directions to LEDs but not distance

For kinematics calculations:
- Sensor frame aligned with sensor lens axes
- Moving flotor frame
- Sensors A, B, and C
Sensor Housing:

- Designed by Zack Butler
- 2.5:1 demagnifying lens
- Sensor signals determine light spot position indicating direction to LED marker but not distance
- LED spot position approximately proportional to difference over sum of opposing electrode currents on PSD:
Sensor Calibration:

- Sensor signals nonlinearly warped towards sensor edge
- Calibration data obtained using XY stage to move LED
- Data reinterpolated to obtain lookup tables to transform signal back to LED positions
- 2D interpolation of LUT done each control update
Sensing Kinematics:

For position \([x \ y \ z]\) and axis-angle rotation \([\theta \ n1 \ n2 \ n3]\), spot positions are:

\[
S_{a,x} = \frac{ll_1[n_1n_3(1-\cos\theta) - n_2\sin\theta] + z}{l_1[n_1^2 + (1-n_1^2)\cos\theta] + x + l_z - l_t}
\]

\[
S_{a,y} = \frac{ll_1[n_1n_2(1-\cos\theta) - n_3\sin\theta] + y}{l_1[n_1^2 + (1-n_1^2)\cos\theta] + x + l_z - l_t}
\]

With \(l_z\) lens to sensor distance, \(l\) origin to lens, \(l_t\) origin to sensor

Fast iterative method from Stella Yu to solve position from sensor signals:

- Directions of light beam vectors known but not magnitudes
- Previous solution as initial estimate for iteration
- \(<0.001\) mm error after 2 iterations in simulation
Haptic Device Control:

- PD control for 6 DOF axes
- 1500 Hz maximum sample and control rate with onboard 68060 processor
- Hard software limits to prevent overrotation
- Routines for smooth takeoff and landing
Performance Parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flotor mass:</td>
<td>550 g</td>
</tr>
<tr>
<td>Maximum forces:</td>
<td>55 N in all directions</td>
</tr>
<tr>
<td>Maximum torques:</td>
<td>6.3 N-m in all directions</td>
</tr>
<tr>
<td>Translation range:</td>
<td>25 mm</td>
</tr>
<tr>
<td>Rotation range:</td>
<td>15-20° depending on position</td>
</tr>
<tr>
<td>Maximum stiffness:</td>
<td>25.0 N/mm</td>
</tr>
<tr>
<td>Position resolution:</td>
<td>5-10 micrometer</td>
</tr>
<tr>
<td>Power consumption:</td>
<td>2.5 W</td>
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</tbody>
</table>
Frequency Responses:

**Force bandwidth:**
- flotor mounted on load cell
- Resonance at ~250 Hz

**Closed-loop position bandwidth:**
- >100 Hz for all DOF at 1300 Hz control rate
- Vertical translation results shown
Interaction with Simulations:

- Close integration between simulation and device controller needed for effective haptic interaction system
- **Virtual tool** in simulation corresponds to **flotor handle** of device
- **Virtual coupling** and **contact point intermediate representation** methods
Physically-Based Simulation:

CORIOLIS simulation package developed by Baraff at CMU for efficient collision detection and dynamic simulation of nonpenetrating rigid objects in near real time:

Execution on SGI workstation:

- Environments up to 10 objects of 6-12 vertices
- 2nd order Runge Kutta integration for speed
- 100 Hz update rate using timer signal handler
- Graphics update at 15-30 Hz
Coulomb stick/slip friction used for surface contacts:

- During sticking: \( f = -k_v x - k_p (x_d - x) \)
- During slip: \( f = -k_v x \)
- Stick/slip force threshold: \( f_f = \mu f_n \)

Texture can be emulated with depth map (a), shape feature interpenetration (b), or stochastic models (c):

- Interpenetration model used for maglev haptic device
- Constraint, texture, and friction forces superimposed during interaction
Haptic User Interface Features:

Tool, environment, and mode selection

Simulation, material, and coupling parameter controls

User-variable scaling and offsets between device and simulation

Control modes implemented to move virtual tool arbitrarily large distances and rotations in simulated environment:

- Rate-based control
- Viewpoint tracking
Local Simulations:

- Simulations computed on control processor
- Host workstation for graphics display only
- Fastest response rate but limited environment simulation due to limited computational power

Enclosed Cube

Surface Texture and Friction
Physical Simulation Environments:

- Physically based dynamic rigid body simulation on host
- Virtual coupling and contact point intermediate representation used to integrate simulation with haptic device controller

**Peg-in-Hole, Key and Lock, Blocks World Environments**
Virtual Coupling for Haptic Interaction:

- Position data exchanged between host and controller each simulation update
- Device handle and virtual tool each servo to setpoints from the other system:
  \[ f_{dev} = f_g + K_p(x_{tool} - x_{dev}) + K_v r(x_{dev} - x_{devprev}) \]
  \[ f_{tool} = f_{other} + K_{spring}(x_{dev} - x_{tool}) + K_{damp} v_{tool} \]
- Interpolation of simulation setpoints prevents sliding contact jitter when device position bandwidth is greater than simulation rate
- System easily stabilized by adjustment of coupling gains
Virtual Coupling Peg-in-Hole Results:

Square peg insertion with virtual coupling, 0.02 mm clearance:

- 6 stages of insertion task
- Rotation and torque response at impact with hole edge
Virtual Coupling Peg-in-Hole Results:
Square peg insertion with virtual coupling, 0.02 mm clearance:

Rotation:
Virtual Coupling Peg-in-Hole Results:

Square peg insertion with virtual coupling, 0.02 mm clearance:

Force:

[Diagram showing force over time with various stages labeled such as 'free motion', 'sliding on surface', 'sliding in hole', 'at hole bottom', 'released', and 'shaken by user'.]
Virtual Coupling Peg-in-Hole Results:
Square peg insertion with virtual coupling, 0.02 mm clearance:

Torque:

![Graph showing torque over time with phases labeled: free motion, sliding on surface, sliding in hole, at hole bottom, released, shaken by user.](chart)

Time (secs)
Contact Point Intermediate Representation:

- For faster, more accurate response
- List of contact points sent from simulation to controller with position setpoint
- Force and torque feedback applied from each contact point
- Edge & face contacts from multiple vertex contacts

- Difficult to make stable system with CPIR alone
- Hybrid control implemented, CPIR for translation and VC for rotation
- Simulation setpoints also used to add friction emulation
Hybrid CPIR Peg-in-Hole Results:

Square peg in hole insertion with hybrid CPIR, 0.02 mm clearance:

- More detail than virtual coupling
- Dramatically sharper feel
Hybrid CPIR Peg-in-Hole Results:
Square peg in hole insertion with hybrid CPIR, 0.02 mm clearance:

Rotation:
Hybrid CPIR Peg-in-Hole Results:
Square peg in hole insertion with hybrid CPIR, 0.02 mm clearance:

Force:

![Graph showing force vs time](image)

- X_force
- Y_force
- Z_force

Time (secs)
Hybrid CPIR Peg-in-Hole Results:
Square peg in hole insertion with hybrid CPIR, 0.02 mm clearance:

Torque:
Summary of System Operation:

Each cycle of the device controller: (1000 Hz hard realtime)
- Sensor sampling
- Kinematics Calculation
- Forces & torques generated from simulation setpoints
- Local interaction forces added (texture/friction)
- Conversion to currents to amplifiers
- If data received from host, reply

Each cycle of the host workstation simulation: (100 Hz soft realtime)
- Virtual tool simulation data sent to device controller
- Device handle position read from controller
- Simulation state updated
- List compiled of virtual tool contact point data

User interface and graphics update updated separately (15-30 Hz)
Conclusion:

Contributions:

Device:
- Design for high position resolution and control bandwidths
- Measured performance
- Testbed for simulation and interaction software development

Software:
- Simulation methods
- Integration methods between simulation and controller
- Haptic user interface development

Future Research Directions:
- Psychophysical perception studies
- Increased realism and complexity of environments
- Application simulations
- Teleoperation
Acknowledgements:

**Ralph Hollis:** thesis advisor, original IBM wrist maglev device

**David Baraff:** CORIOLIS dynamic simulation software package

**Zack Butler:** sensor subassembly design and sum/difference circuits

**Stella Yu:** Sensor kinematic solution

Summer Students **Chris Donohue** for cabinet layout and **Todd Okimoto** for actuator testing
Virtual Coupling Collision Results:

Tool colliding with floor while swept in \(+x\) direction:

- **Position:**
  - \(X_{\text{desired}}, Y_{\text{desired}}, Z_{\text{desired}}\) setpoints from simulation
  - \(X_{\text{pos}}, Y_{\text{pos}}, Z_{\text{pos}}\) maglev device handle positions
  - Setpoint steps due to slower simulation update rate
  - Interpenetration due to limited stiffness of device controller

- **Force:**
Hybrid CPIR Collision Results:

Tool colliding with floor while swept in $+x$ direction:

Position:

Force: