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:

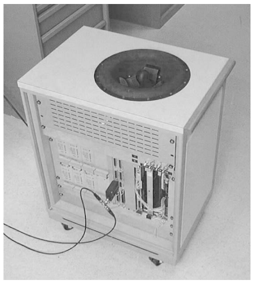
Definition of Terms:

- **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]

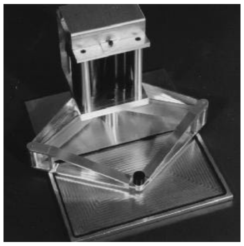
New Maglev Haptic Device:



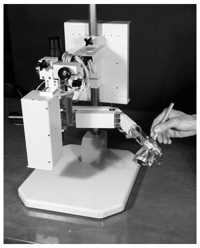
- New Lorentz maglev device developed specifically for haptic interaction
- User grasps and manipulates handle in bowl set in cabinet top

Other Haptic Interface Devices:

PHANTOM
SensAble Tech.



Pantograph
McGill Univ.



Freedom 6S
MPB Tech.

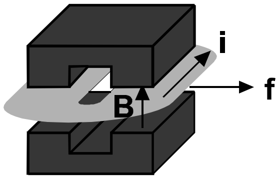
Laparoscopic Impulse Engine
Immersion Corp.

- 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:

$$\mathbf{f} = -\,\mathbf{i} \oint \mathbf{B} \times \mathbf{dl}$$

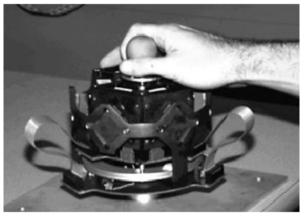


- Position sensing with LEDs and position sensing photodiodes
- 6 actuators needed for levitation

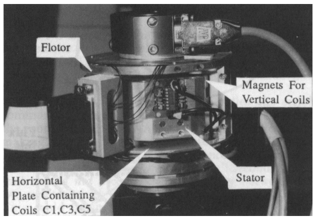
Advantages:
  - Force independent of position
  - Noncontact actuation & sensing, only light cable connection
  - 6 DOF with one moving part

Disadvantages:
  - Limited motion range
  - Expensive materials and sensors

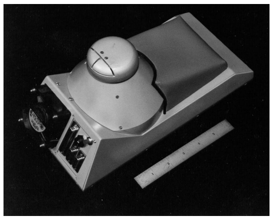
Other Maglev Devices:



IBM Magic Wrist, 1988



UBC Wrist, 1991



UBC Powermouse, 1997

IBM and UBC wrists:

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

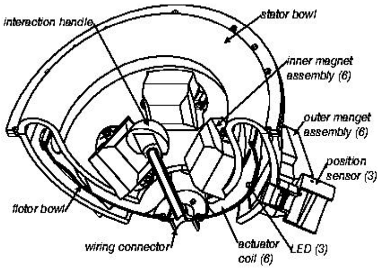
Position bandwidths:	~50 Hz
Position resolution:	1-2 µm
Motion range:	<10 mm, <10º motion ranges

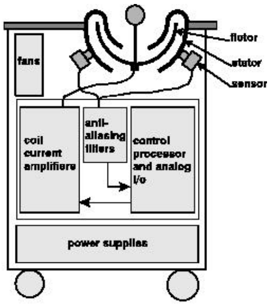
UBC Powermouse recently developed, small cost and motion range

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

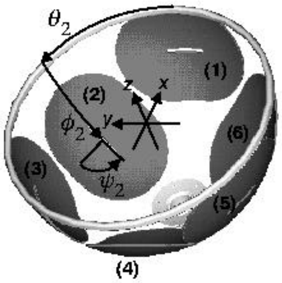
New Device Design:





- 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:



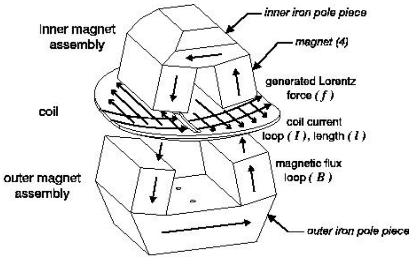
- 115 mm radius fits magnet assemblies, user hand, motion range
- Coil configuration maximizes motion range and force/inertia ratio
- Efficient force and torque in all directions

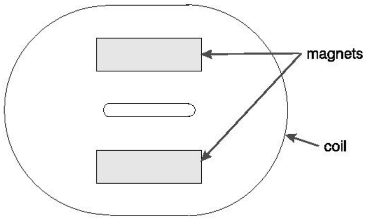
To convert coil currents to force and torque on flotor:

$\boldsymbol{F} = \boldsymbol{AI}$, $\boldsymbol{F} = \{f_x\ f_y\ f_z\ t_x\ t_y\ t_z\}$, $\boldsymbol{I} = \{i1\ i2\ i3\ i4\ i5\ i6\}^T$

$$\boldsymbol{A} = [7.2\ 7.2\ 7.2\ 0.83\ 0.83\ 0.83]\mathrm{x} \begin{bmatrix} -S(-\pi/8) & -S(\pi/3) & -S(2\pi/3)S(-\pi/8) & 0 & -S(4\pi/3)S(-p/8) & -S(5\pi/3) \\ 0 & C(\pi/3) & -S(2p/3)S(-\pi/8) & -1 & -S(4\pi/3)S(-p/8) & C(5\pi/3) \\ C(-\pi/8) & 0 & C(-\pi/8) & 0 & C(-\pi/8) & 0 \\ 0 & -C(\pi/3)S(-\pi/4) & S(2\pi/3) & S(\pi/4) & -S(4\pi/3) & -C(5\pi/3)S(-\pi/4) \\ -1 & -S(\pi/3)S(-\pi/4) & C(2\pi/3) & 0 & C(4\pi/3) & -S(5\pi/3)S(-\pi/4) \\ 0 & -S(\pi/4) & 0 & -S(\pi/4) & 0 & -S(-\pi/4) \end{bmatrix}$$

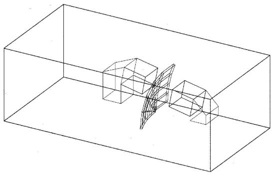
Single Lorentz Actuator:





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

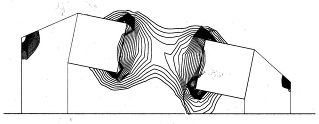
Actuator Design FEA:



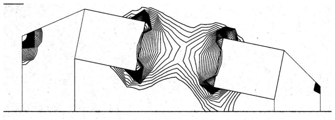
3-D finite element analysis model necessary due to geometry, air gaps, field saturation

- Larger magnets not necessarily better

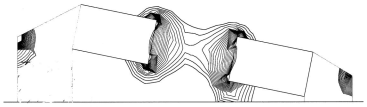
20 mm magnets: 7.58 N/A force



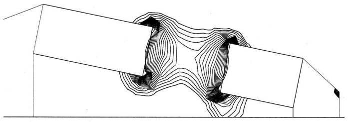
25 mm magnets: 7.98 N/A force



30 mm magnets: 7.60 N/A force

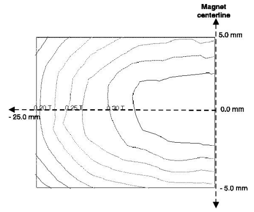


30 and 45 mm magnets: 7.58 N/A force

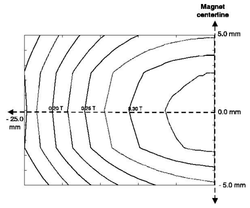


Prototype Actuator Testing:

Magnetic field in center plane between magnet faces:



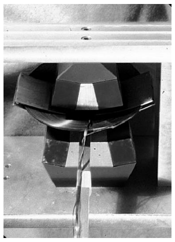
FEA model



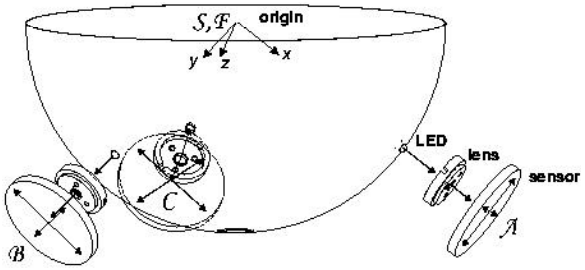
Measured Prototype

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:

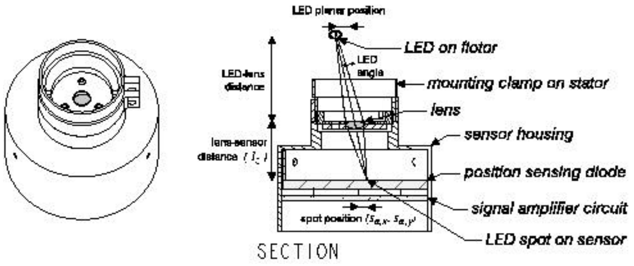


- Fixed lenses image light from LEDs on moving flotor onto fixed planar position sensing photodiodes
- Sensors provide directions to LEDs but not distance

For kinematics calculations:

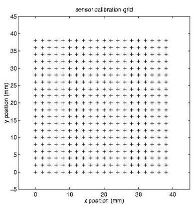
  - Sensor frame aligned with sensor lens axes
  - Moving flotor frame
  - Sensors A, B, and C

Sensor Housing:

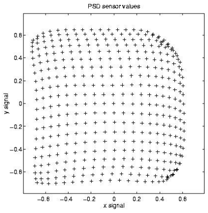


- Designed by Zack Butler
- 2.5:1 demagnifying lens
- Sensor signals determine light spot position indicating direction to LED marker but not distance
- LED spot position approximately proportional to difference over sum of opposing electrode currents on PSD:

Sensor Calibration:



LED position grid for sensor calibration



Sensor output distortion

- 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:

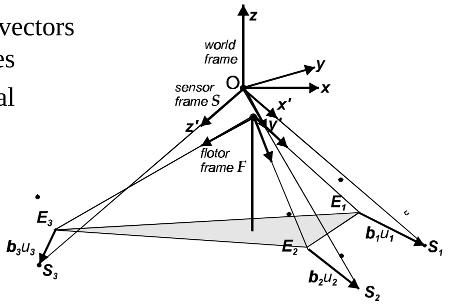
For position [*x y z*] and axis-angle rotation [*q n1 n2 n3*], spot positions are:

$$S_{a,x} = \frac{l_z l_l\,[n_1 n_3(1-\cos q) - n_2 \sin q\,] + z}{l_l\,[n_1^2 + (1-n_1^2)\cos q\,] + x + l_z - l_t} \qquad S_{a,y} = \frac{l_z l_l\,[n_1 n_2(1-\cos q) - n_3 \sin q\,] + y}{l_l\,[n_1^2 + (1-n_1^2)\cos q\,] + x + l_z - l_t}$$

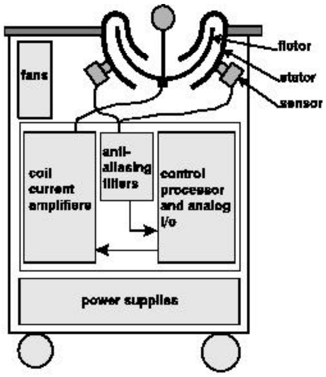
With l_z lens to sensor distance, l origin to lens, l_t origin to sensor

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

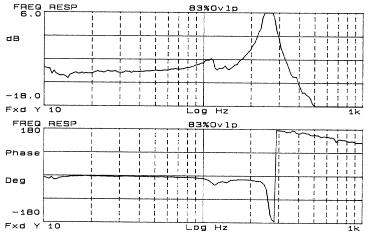
Performance Parameters:

Flotor mass:	550 g
Maximum forces:	55 N in all directions
Maximum torques:	6.3 N-m in all directions
Translation range:	25 mm
Rotation range:	15-20^{o} depending on position
Maximum stiffness:	25.0 N/mm
Position resolution:	5-10 micrometer
Power consumption:	2.5 W

Frequency Responses:

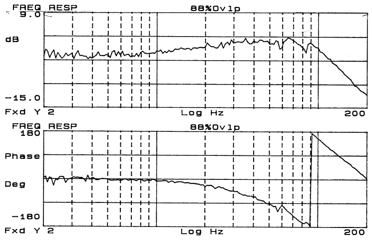
Force bandwidth:

- flotor mounted on load cell
- Resonance at ~250 Hz

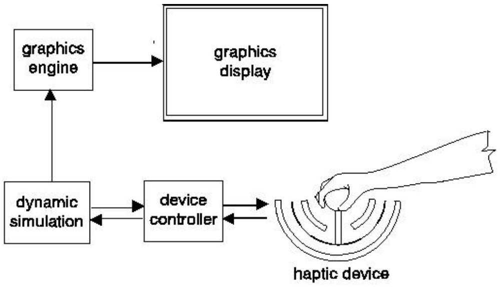


Closed-loop position bandwidth:

- >100 Hz for all DOF at 1300 Hz control rate
- Vertical translation results shown



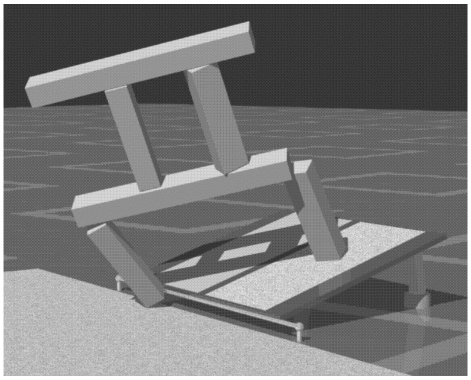
Interaction with Simulations:



- 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:

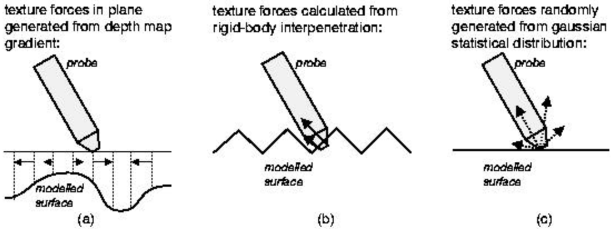
- Environments up to 10 objects of 6-12 vertices
- 2nd order Runge Kutta integration for speed
- 100 Hz update rate using timer signal handler
- Graphics update at 15-30 Hz

Surface Effects:

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: $f_f = m f_n$

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



- Interpenetration model used for maglev haptic device
- Constraint, texure, and friction forces superimposed during interaction

Haptic User Interface Features:

Tool, environment, and mode selection

Simulation, material, and coupling parameter controls

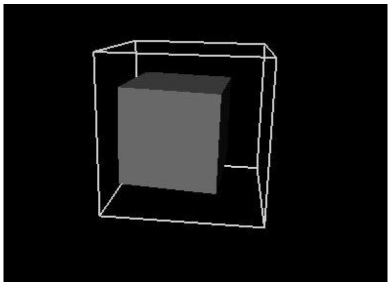
User-variable scaling and offsets between device and simulation

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

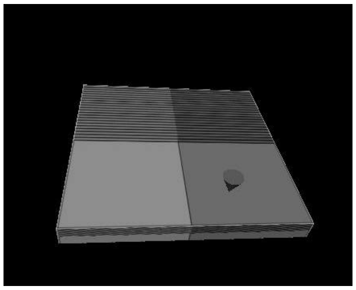
- Rate-based control
- Viewpoint tracking

CamStep 10
Gravity 9.9
Timestep 0.020
Tolerance 0.020
Handstick 0.60
DynFric 0.20
StatFric 0.35
Rebound 0.40
Density 0.75
PosStiff 100
PosDamp 25.0
RotStiff 600
RotDamp 25.0
PosRteTh 30.0
RotRteTh 0.20
ViewDist 60
Height 10
Tool Rot 0.00
PosScale 2.0
RotScale 2.0
PosRate 2.0
RotRate 2.0
X Off 0.0
Y Off 0.0
Z Off 5.0
R Off 0.00
P Off 0.00
Y Off 0.00

Local Simulations:



Enclosed Cube



Surface Texture and Friction

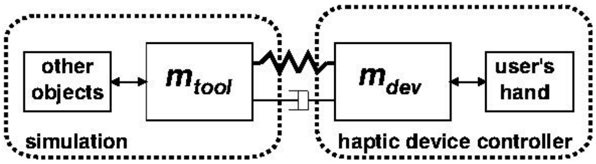
- Simulations computed on control processor
- Host workstation for graphics display only
- Fastest response rate but limited environment simulation due to limited computational power

Physical Simulation Environments:

Peg-in-Hole, Key and Lock,
Blocks World Environments

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

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:

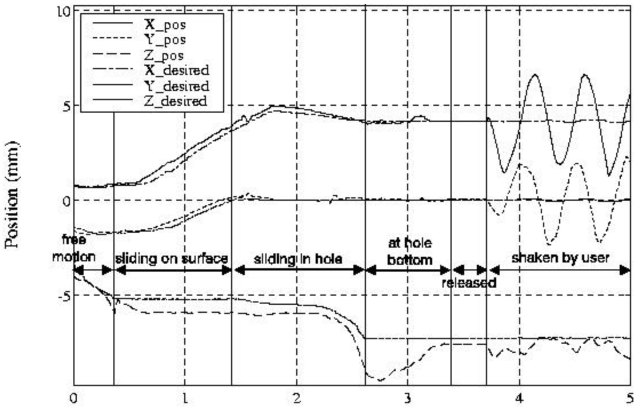
$$f_{dev} = f_g + K_p(x_{tool} - x_{dev}) + K_v r(x_{dev} - x_{devprev})$$
$$f_{tool} = f_{other} + K_{spring}(x_{dev} - x_{tool}) + K_{damp}\, v_{tool}$$

- 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:

Position:

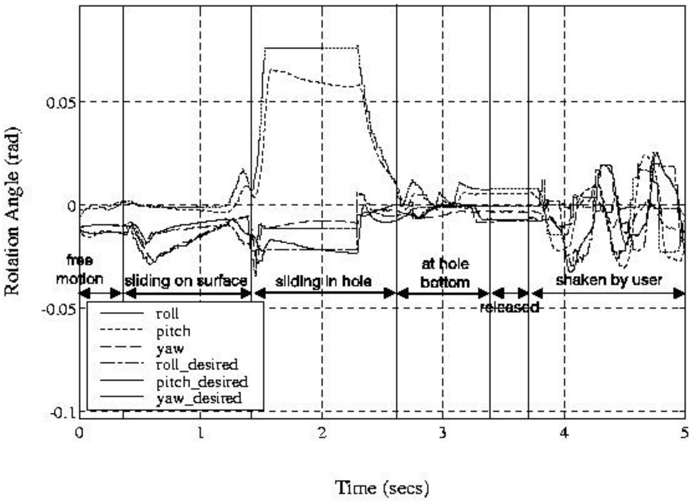


- 6 stages of insertion task
- Rotation and torque response at impact with hole edge

Virtual Coupling Peg-in-Hole Results:

Square peg insertion with virtual coupling, 0.02 mm clearance:

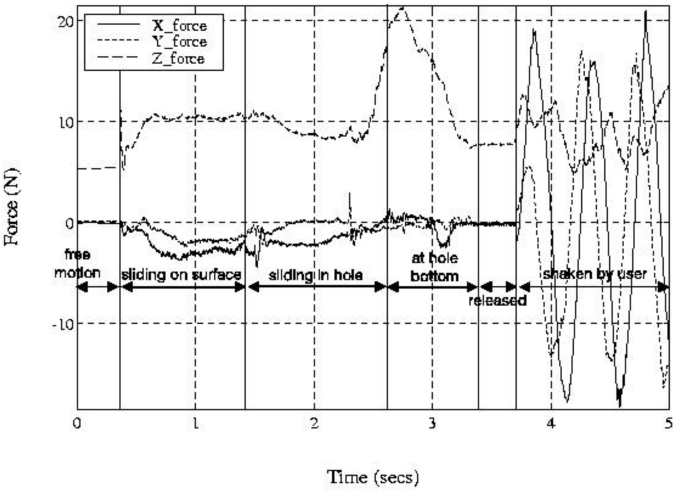
Rotation:



Virtual Coupling Peg-in-Hole Results:

Square peg insertion with virtual coupling, 0.02 mm clearance:

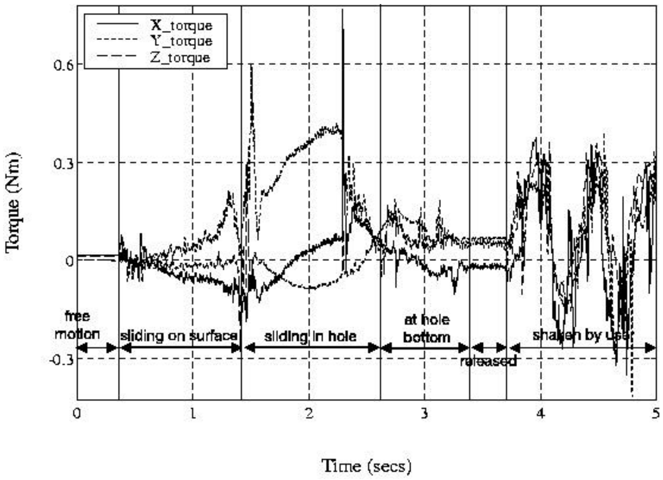
Force:



Virtual Coupling Peg-in-Hole Results:

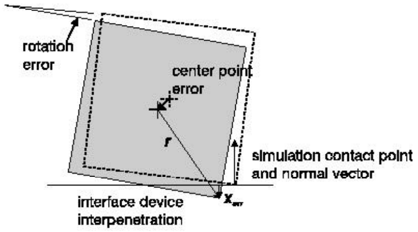
Square peg insertion with virtual coupling, 0.02 mm clearance:

Torque:



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

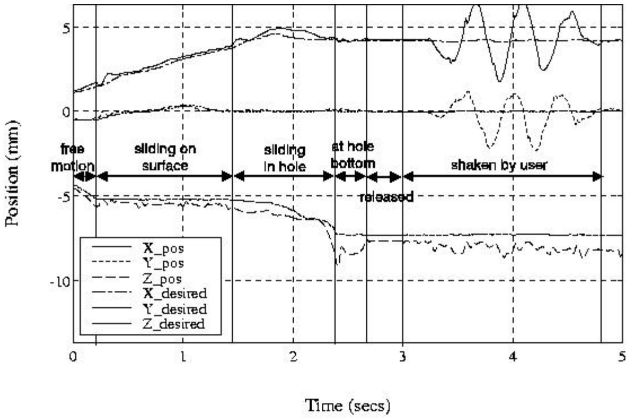


- Difficult to make stable system with CPIR alone
- Hybrid control implemented, CPIR for translation and VC for rotation
- Simulation setpoints also used to add friction emulation

Hybrid CPIR Peg-in-Hole Results:

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

Position:

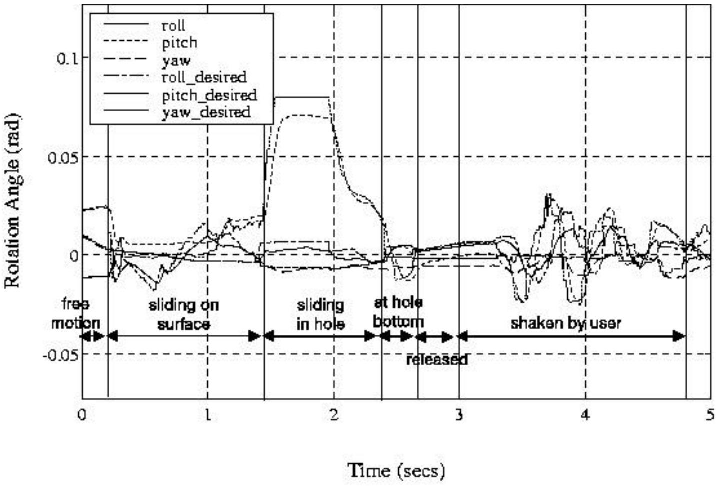


- More detail than virtual coupling
- Dramatically sharper feel

Hybrid CPIR Peg-in-Hole Results:

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

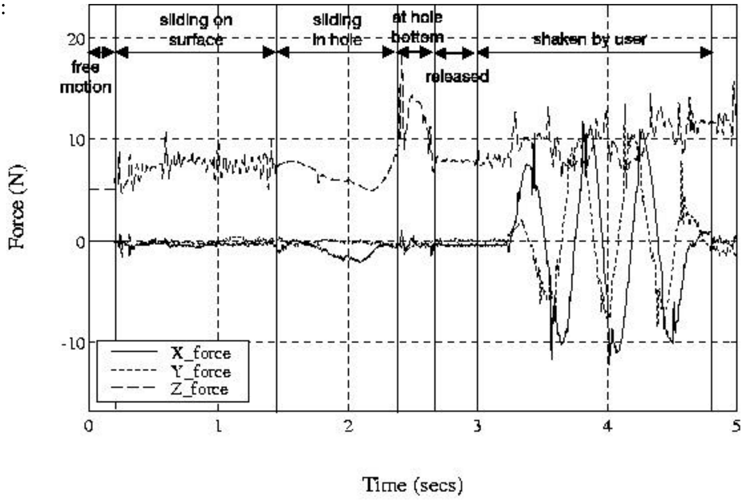
Rotation:



Hybrid CPIR Peg-in-Hole Results:

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

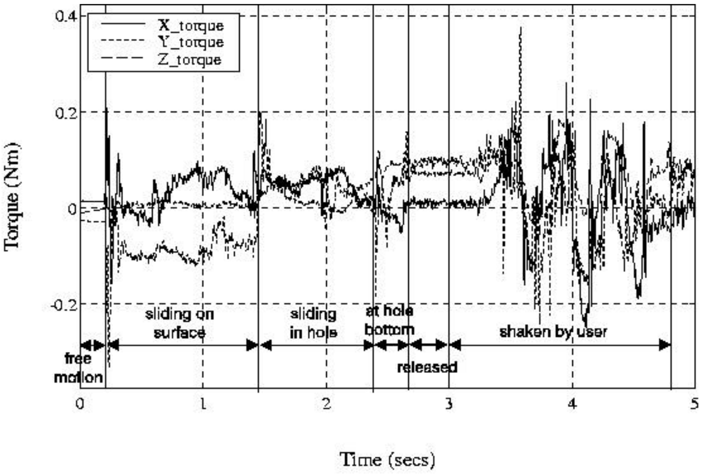
Force:



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

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David Baraff: CORIOLIS dynamic simulation software package

Zack Butler: sensor subassembly design and sum/difference circuits

Stella Yu: Sensor kinematic solution

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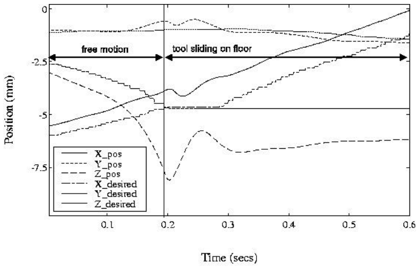
Virtual Coupling Collision Results:

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

Position:



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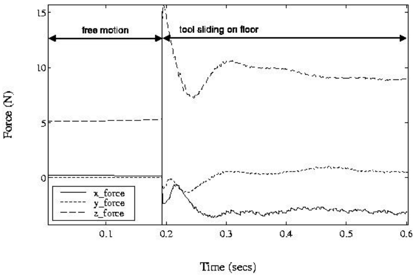
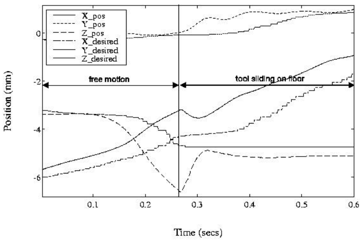


- *X_desired, Y_desired, Z_desired* setpoints from simulation
- *X_pos, Y_pos, Z_pos* maglev device handle positions
- Setpoint steps due to slower simulation update rate
- Interpenetration due to limited stiffness of device controller

Hybrid CPIR Collision Results:

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

Position:



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