Haptics

Haptics – Science of Touch
- Haptics from Greek
  - \( \alpha \phi \eta \) = touchable
  - Scientific description of touch, the sense
  - Has nothing to do with computers and games
  - Self perception and perception of the world
- Multi- and crossdisciplinary
  - Old research area
  - Psychophysics
  - Control theory and system identification
  - Computer science

Synopsis
- Haptics – background, motivation, research
- Haptics in computer science and VR
- The senses, important aspects
- Haptic devices
- Haptic rendering

Psychophysics
- Applied biology and psychology
  - Limits of haptic senses
  - Haptic memory and processing
- Computers are their tools
  - Haptics has little to do with computers
  - Use computer to perform controlled experiments
  - However: why simulate what you have in real?
Control Theory

- Robotic control
  - Applied haptics in robotics
  - Tele operations (remote control)
  - Stability, performance, latency, etc
- Development of hardware
  - devices and haptic rendering

Motivation in VR

- Increased body control
  - Coordination
  - Speed and precision
- Guidance
  - Pathways, tutoring
  - Physical support
- Information
  - Additional channel
  - Hardness, strength, position
  - Reinforce visual impression

Taxonomy for GUI

- Miller & Zeleznik
  - GUI enhanced with haptics
  - Natural and better control
- Basic modes
  - Anticipation
  - Follow-through
  - Indication
  - Guidance
  - Directions
- Extend to 3D VR interactions

Applications

- Haptics more important in some cases
  - Where vision is poor or not available
  - Where touch is of other importance
- Some examples
  - Bone drilling
  - Spinal anaesthesia
  - Virtual prototyping
  - Stroke rehab
Bone Drilling
- Poor visibility / no visibility

Spinal Anaesthesia
- Feel the tissues
  - Push towards membrane
  - Pop through and stop!

Virtual Prototyping
- How will it work?
  - Cheap(er) realization of prototype
    - Connect to CAD/CAM system
    - Easy to update minor changes, adjust parameters
  - Test feel, ergonomics, assembly, etc

Stroke Rehab
Two Haptic Senses

- Tactile senses (cutaneous)
  - Nerves under skin
  - Pressure, shear, slip
    - Micro shape, vibrations, etc
  - Temperature, pain
- Kinaesthetic senses (proprioception)
  - Nerves in muscles and joints
  - Forward kinematics
  - Position, force, macro shapes, weight

Building One Sense

- A single whole
  - Even kinaesthetic devices give tactile stimulation
- Exploratory procedures
  - Identified modes of interaction
    - Lateral motion
    - Pressure
    - Static contact
  - Unsupported holding
  - Enclosure
  - Contour following
- Identifies properties of objects
- Important in design of VR interaction and rendering

Haptic Illusions

- Body size and posture
  - Touch with fingers crossed
  - Stimulate muscles → illusion of motion → illusion of size change
  - Tactile distances vary over skin surface
- Shapes
  - Fishbone/comb illusion
  - Rotational error
  - After-effects
- SNR-based mix between senses

Tactile Characteristics

- Micrometer precision
  - Feel a the edge of a paper on a flat surface
  - Feel difference on directions and tilting
- Vibrations
  - Large range – sensing 20–1000 Hz
  - Very small magnitude
- Temperature
  - Termoconductivity
  - Heat, cold
- Pain!
**Tactile HID**

- Feedback from computer
  - Simulate sensations
  - Indicate events
  - No input, but put on mice, etc
- Many types, for example
  - Vibrotactile
  - Surface
  - Pin-based
  - Electrocutoaneous

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**Vibrotactile Devices**

- Vibrating elements
  - Based on motor or speaker
  - Distributed over body
  - Put into objects, e.g. input devices

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**Vibrotactile Devices**

- Applications
  - Indicate direction
    - Vibrations in sequence
    - Intuitive perceptualization
  - Indicate event
    - Warning signal
    - Simulate follow through on touch screens
  - Indicate closeness
    - Varying magnitude
    - Discrimination threshold is not very good

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**Surface-based Devices**

- Real surface
  - Pushing, shearing
- Simulate touch
  - Pressure against surface
  - Slipping
  - Also closeness if you like
- Crude
  - Poor realizations
### Pin-based Tactile Devices
- Pins sticking out of surface
  - Typically > 5x5 pins
  - Pushing or vibrating
  - Magnitude in millimeter range
- Indicating shapes
  - Ridges and edges can be simulated
  - Moving vibrations can be felt as slipping
- Typically large
  - Pneumatic, servos, electromagnetic
  - Hard to fit on mice or other devices

### Electrocutaneous Devices
- Electrocutaneous
  - Electric stimulation of nerves
    - Anodes and cathodes
  - Feeling of touch, slipping
    - Showing shapes, edges
    - Sequences to represent motion
  - Small form factor
- Issues
  - Conductivity dependent
    - Salt, sweat, pressure
  - Pain!

### Kinaesthetic Characteristics
- Input/output
  - Connection between motoric and sensory systems
    - Parietal cortex – sensing, data integration, manipulation
  - Coordination
  - Balance between inner and outer forces
- Low resolution
  - Precision in centimeter range
- Dynamic system
  - Manipulation at about 1–10 Hz
  - Low cognitive attention below 1 Hz

### Kinaesthetic HID
- 3D input device with feedback
  - Degrees-of-freedom
    - Both input and output
    - Important for what to simulate
- Two control paradigm
  - Impedance control – force feedback
  - Admittance control – position feedback
- Important characteristics
  - Precision, strength
  - Mechanical stiffness, Z-width
**Force Feedback Control Basics**

- Closed loop control system
  - Feedback force affects position
  - Dynamic, hybrid non-linear system
  - Require high update rates, typically 1 kHz
- Warning
  - For high loop gain
    - Stiff system causes instability
    - Caused by high stiffness in simulation
  - For phase shifts
    - Caused by feedback delay
    - Caused by low mechanical stiffness

**Grounded / Ungrounded**

- **Grounded devices**
  - Provide force/torque feedback relative world
  - Lean against wall
- **Ungrounded**
  - Grounded on body
  - Using inertia

**Force Feedback Controls**

- Add motor to your control
  - Force feedback steering wheels
  - Force feedback joysticks
  - Often playback
    - Higher stability
    - Lower quality
- Issues
  - Typically low quality feedback
  - Not much use in VR
**Force Feedback Wand/Stylus**

- Single mechanical arm
  - Sensable
    - Desktop PHANTOM
    - Premium PHANTOM
    - PHANTOM Omni
  - Multiple mechanical arms
    - Force Dimensions
      - Delta
      - Omega
    - Haption
      - Virtuose 6D

**Device Characteristics**

- Very high precision
  - Required for stable interaction
  - Measured in micrometers
  - Typically cheap, but you get what you pay for
- Force feedback
  - Light devices
  - Varying strength, typically < 8 N
- 6 DoF – torque feedback
  - Low strength, typically < 0.5 Nm
  - Limited motion
  - Backdrive friction (gears and such)
  - Large and heavy stylus

**More Force Feedback**

- MagLev
  - Magnetism-based
  - Very strong
  - Large device
  - Miniature working space
- Spidar
  - Strings
    - 4 = 3 DoF, 8 = 6 DoF
    - Occlusion problem
    - String stiffness problem

**Other Force Feedback Devices**

- Large variation
  - Much research
  - Not much commercial
Position Feedback Control Basics

- Admittance
  - Force sensors and explicit position control
    - Handle virtual weight, dynamics
    - Simulate acceleration from input force
  - Don't admit penetration of stiff walls
    - Simulated stiffness limited by mechanical stiffness

Special Considerations in VR

- Workspace size
  - Haptic devices are typically small
    - Long mechanical arms have poor stiffness
  - Mobile haptic devices
  - Wearable haptic devices (ungrounded)
- Occlusion
  - Mechanical arm might be in your way
  - Interference with other tracking
    - Magnetic, sound or image-based

Asynchronous Rendering

- Graphics rendering
  - Traverse scene graph (@ 10–100 Hz)
  - Much processing, graphics, events, etc
- Haptic rendering
  - High update rate, typically 1 kHz
  - Shared or separate scene graph
  - Separate, asynchronous thread (process?)
  - Synchronization issues
**Haptic Rendering**

- Software to generate haptic feedback
  - Consider kinaesthetic force feedback only
    - Most common, most practical
  - Impedance control algorithm
    - Position input – force output
- Geometry rendering
  - Penalty-based, god object-based, proxy-based
  - Polygons, implicit surfaces, nurbs, etc.
- Volume haptics
  - Haptic rendering of non-surface data

**Important Properties**

- Mass
  - Inertia, momentum
  - Moment of inertia
  - Wrong behaviour kills the illusion
- Surface properties
  - Friction
    - Dynamic and static
  - Hardness
  - Textures
  - Wrong properties causes misinterpretations

**Important Characteristics**

- Smooth
  - No discontinuities
- Conservative
  - Do not add energy
  - Passive behaviour
  - Stable behaviour
- No artifacts
  - Haptic behaviour should reflect the properties
  - No vibrations, jitter or other misbehaviour

**Penalty-based Haptic Rendering**

- Penalty for penetration
  - Find shortest way out
  - Push haptic instrument out
    - Force dependent on penetration depth
    - "Stiffness" (N/m)
- Issues
  - Force discontinuities
  - Pop-through
  - Simplistic
    - no friction, texture, etc.
God object-based Rendering

- Point tracing the polygons
  - Spring to calculate feedback
    - Stiffness (N/m)
  - No pop-through
  - Friction cone
- Issues
  - Fall-through "between" polygons
  - No contact size, only point
  - Hardware accelerated
  - No topology information

Proxy-based Haptic Rendering

- Ruspin
erenderer
  - Finite-sized proxy sphere
    - Configuration space
    - Iteratively update proxy position
  - PD regulator
    - No integration – why?

Speed and Update Rates

- Fast polygon processing
  - Find closest, find configuration space, etc.
  - Hierarchical bounding spaces
  - Local haptic surface
    - Update cache at 50 Hz
    - Haptic rendering on cache at 1 kHz
- Issues
  - Synchronization
  - Size of cache vs. size of movements
  - Motion and prediction

Friction and Force Shading

- Force shading
  - Interpolated normal
  - Modulate proxy motion
- Friction
  - Limit length the proxy may travel
  - \[ \ddot{x} = \frac{f_i - \mu f_n}{b} \]
- Bump-maps
  - Gray texture or selected channel
  - Modulate normal by image gradient
### Roughness
- Simplified simulation
  - Miniature bumps = no spatial correlation
  - Random force modulation
    - Gaussian noise
    - Magnitude and deviation parameters
  - Fast computations and natural feeling

### Event-based Force Feedback
- The haptic senses are dynamic
  - Stimulated by changes
  - Low cognitive response to low frequency changes
  - Even sense of transiental vibrations
- Event-based haptics
  - Low frequency response
    - Proxy-based
    - Low stiffness, high stability
  - Add transient vibrations
    - Event and material specific
    - Apply inverse device transfer function

### Volume Haptics
- For scientific/medical visualization
  - Volumetric data (CT, MRI, CFD, etc)
  - Complex data, hard to understand
  - Use VR and haptics to examine
    - Additional freedom in exploration
    - Haptics for information and guidance
- Basic principles
  - Surface metaphor
  - Force functions
  - Shape representations

### Surface Metaphor
- "Occupancy" volume or implicit function
  - Extracted geometry and use surface rendering
  - Render surface from interfaces in volume
    - Direct Volume Haptics (DVH)
- Uses in simulators
  - Virtual prototyping
  - Bone drilling/milling
**Force Functions**

- Push haptic instrument
  - Force vector as function of data
  - Gradient, viscosity, etc
  - Static control, \( \vec{a} = F(\vec{V}(\vec{x}), \vec{x}) \)
  - Added memory = dynamic control

\[
\vec{a} = C_1 \hat{\vec{V}}(\vec{x}) + C_2(\vec{V}(\vec{x})) \hat{\vec{x}}
\]

\[
\vec{a} = C_3(|\vec{V}(\vec{x})|) |\hat{\nabla} \times \vec{F}(\vec{x})| \times \vec{F}(\vec{x})
\]

**Shape Representations**

- Render shapes
  - Many different metaphors for data representation
  - Basic haptic primitives
    - One for each manifold dimensionality
    - Point, line plane (and force)
  - Control parameters as functions of data
    - Strength and direction
    - The function controls the feeling
    - Adapt function after data, contents, user and purpose

**Summary**

- Haptics – two senses in one
- Psychophysics
  - Aspects, functionality, illusions
- Control theory
  - Control loops, Z-width, admittance, impedance, dynamic hybrid system
- Devices
  - Admittance, impedance, tactile, grounded, etc
- Haptic rendering
  - Geometry, volumes, shading, artifacts, bump-map