3D User Interface Techniques for Selection and Manipulation

Lecture #9: Selection and Manipulation
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Interaction Workflow

User

Human transfer function
Percepts → User goals

User goals → Actions

Display → Perceptual information

Input Device

Actions → Signals

System

System transfer function
Signals → System goals

Output Device

System goals → Display
3D Interaction Techniques

- Choosing the right input and output devices not sufficient for an effective 3D UI
- Interaction techniques: methods to accomplish a task via the interface
  - Hardware components
  - Software components: control-display mappings or transfer functions
  - Metaphors or concepts
- Universal tasks: selection and manipulation, travel, system control

Overview

- Manipulation: a fundamental task in both physical and virtual environments
- 3D manipulation task types
- Classifications of manipulation techniques
- Techniques classified by metaphor:
  - Grasping
  - Pointing
  - Surface
  - Indirect
  - Bimanual
  - Hybrid
3D Manipulation Tasks

- Broad definition: any act of physically handling objects with one or two hands
- Narrower definition: spatial rigid object manipulation (shape preserving)

Canonical Manipulation Tasks

- **Selection**: acquiring or identifying an object or subset of objects
- **Positioning**: changing object’s 3D position
- **Rotation**: changing object’s 3D orientation
- **Scaling**: uniformly changing the size of an object
### 3D Manipulation Tasks

#### Canonical Manipulation Tasks

- **Task parameters**

<table>
<thead>
<tr>
<th>Task</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection</td>
<td>Distance and direction to target, target size, density of objects around the target, number of targets to be selected, target exclusion</td>
</tr>
<tr>
<td>Positioning</td>
<td>Distance and direction to initial position, distance and direction to target position, translation distance, required precision of positioning</td>
</tr>
<tr>
<td>Rotation</td>
<td>Distance to target, initial orientation, final orientation, amount of rotation, required precision of rotation</td>
</tr>
</tbody>
</table>

#### Application-Specific Manipulation Tasks

- Canonical tasks can fail to capture important task properties for real applications
- Ex: positioning a medical probe relative to virtual models of internal organs in a VR medical training application
- Techniques must capture and replicate minute details of such manipulation tasks
3D Manipulation Tasks

Manipulation Techniques and Input Devices

- Number of control dimensions
- Integration of control dimensions
  - Multiple integrated DOFs typically best for 3D manipulation
- Force vs. position control
  - Position control preferred for manipulation
  - Force control more suitable for controlling rates

- Device shape
  - Generic vs. task-specific
- Device placement/grasp
  - Power grip
  - Precision grip
    - Use fingers
    - Reduce clutching
Classifications for 3D Manipulation

- Isomorphic (realistic) vs. non-isomorphic (magic)
- Task decomposition
- Metaphor

Grasping Metaphors

**Hand-Based Grasping**

- Simple virtual hand
- Go-Go

\[ r_p = F(r_r) = \begin{cases} r_r & \text{if } r_r \leq D \\ r_r + \alpha(r_r - D)^2 & \text{otherwise} \end{cases} \]

where \( r_r \) = length of \( \vec{r}_p \)
\( r_p \) = length of \( \vec{r}_v \)
\( D, \alpha \) are constants
Grasping Metaphors

Finger-Based Grasping

- Rigid-body fingers
- Soft-body fingers
- god fingers

Rigid-body fingers (Borst and Indugla 2005)

- Need to track the hands and fingers (e.g., bend sensing glove or 3D depth camera)
- Map hand and finger positions to virtual hand and fingers
- Physics-based interactions
  - use virtual torsional and linear spring dampers
  - dynamically influence mapping between real and virtual hands
- Can be “sticky” – difficult to precisely release objects
- Sticky object problem can be reduced with better heuristic-based release functions
Grasping Metaphors

**Soft-Body Fingers (Jacobs and Froehlich 2011)**
- Use deformable representations for virtual fingers
- Lattice shape matching algorithm
  - deform the pads of virtual fingers to dynamically adapt to shapes of grasped objects
  - when real fingers initially collide with virtual objects, virtual finger pads deform slightly
  - when real fingers penetrate inner space of virtual objects, more points of collision produced for virtual fingers
- Implicit friction model compared to rigid body model

**God Fingers (Talvas et al. 2013)**
- god object – a virtual point that adheres to rigid body physics and never penetrates virtual objects (remains on their surface)
  - force direction can be easily calculated
- Goal is to use god-objects for finger grasping and manipulation
  - compute contact area about god-object point as if surface was flat
  - contact area fitted to geometry of the object based on god object force direction
  - odd deformations are prevented by using angular threshold between force directions and surface normals
Grasping Metaphors

Enhancements for Grasping Metaphors

- 3D bubble cursor
- PRISM
- Hook
- Intent-driven selection

3D Bubble Cursor (Vanacken et al. 2007)

- Semi-transparent sphere that dynamically resizes itself to encapsulate the nearest virtual object
- Designed for selecting a single object
- When sphere is too large and begins to intersect a nearby object a second semi-transparent sphere is created to encapsulate that object
Grasping Metaphors

**PRISM (Frees and Kessler 2005)**
- Precise and Rapid Interaction through Scaled Manipulation
- Apply scaled down motion to user’s virtual hand when the physical hand is moving below a specified speed
  - decreased control to display gain
  - increased precision
- Causes mismatch between virtual and physical hand location
  - use offset recovery mechanism based on hand speed
  - allows virtual hand to catch up to physical

**Hook (Ortega 2013)**
- Supports object selection of moving objects
- Observe relationship between moving objects and the hand to develop tracking heuristics
  - compute distance of hand to each virtual object
  - orders and scores targets based on increasing distance
  - close targets have scores increased, far targets have scores deceased
- When selection is made, target with highest score is selected
Grasping Metaphors

Intent-Driven Selection (Periverzov and Llies 2015)
- Use posture of virtual fingers as confidence level in object selection
- Proximity sphere is positioned within grasp of virtual hand
  - virtual fingers touch the sphere
  - anything within the sphere is selectable
- As hand closes, additional proximity spheres are made to specify a smaller subset of selectable objects until one target is selected

Pointing Metaphors

- Pointing is powerful for selection
  - Remote selection
  - Fewer DOFs to control
  - Less hand movement required
- Pointing is poor for positioning
- Design variables:
  - How pointing direction is defined
  - Type of selection calculation
Pointing Metaphors

Vector-Based Pointing Techniques

- Ray-casting
- Fishing reel
- Image-plane pointing

Ray-casting

- Simple pointing technique
- Point at object with virtual ray
  - virtual line indicates direction (e.g., laser pointer)
  - size of the virtual line can vary
- Perform ray casting to select desired object
- Precision can be compromised with far away objects
Pointing Metaphors

**Fishing Reel**
- Additional input mechanism to control the virtual ray
- Select with ray casting and real the object back and forth using additional input (e.g., slider, gesture)

**Image Plane Pointing (Pierce et al. 1997)**
- Image plane techniques simplify object selection by using 2 DOF
  - select and manipulate objects with their 2D projections
  - use virtual image plane in front of user
  - simulate direct touch
- Used to manipulate orientation, not position
- Examples include Head Crusher, Lifting Palms, Sticky Finger, and Framing
Pointing Metaphors

Volume-Based Pointing Techniques
- Flashlight
- Aperture
- Sphere-casting

Flashlight
- Provides soft selection and does not require as much precision
- Instead of using a ray, a conic selection volume is used
- Apex of cone is at the input device
- Object does not have to be entirely within the cone
- Must deal with disambiguation issues
  - choose object closer to the centerline
Pointing Metaphors

**Aperture Selection (Forsberg et al. 1996)**
- Modification of flashlight technique
- User can interactively control the spread of the selection volume
- Pointing direction defined by 3D position of user’s viewpoint (tracked head location) and position of a hand sensor
- Moving hand sensor closer or farther away changes aperture

**Sphere Casting**
- Define position of predefined volume at the intersection of a vector used for pointing and the VE
- Modified version of ray casting
  - casts sphere onto nearest intersected surface
Pointing Metaphors

Enhancements for Pointing Metaphors
- Bendcast
- Depth ray
- Absolute and relative mapping

Bendcast (Riege et al. 2006)
- Pointing analog to 3D bubble cursor
- Bends the pointing vector toward object closest to the vector’s path
  - point line distance from each selectable object is calculated
  - circular arc used to provide feedback
Pointing Metaphors

**Depth Ray (Vanacken et al. 2007)**
- Used to disambiguate which object the user intends to select when pointing vector intersects multiple targets
- Uses depth marker along the ray length
- Object closest to the marker is selected
- User can control marker by moving a tracked input device back or forward

**Absolute and Relative Mapping (Kopper et al. 2010)**
- Useful in dense environments
- Provides manual control of control to display gain ratio of pointing
  - Lets users increase the effective angular width of targets
- Can give user impression of slow motion pointer
Surface Metaphors

Surface-Based 2D Interaction Techniques
- Dragging
- Rotating

Surface-based 3D Interaction Techniques
- Pinching
- Void shadows
- Balloon selection
- Corkscrew widget
- Triangle cursor
Indirect Metaphors

**Indirect Control-Space Techniques**
- Indirect touch
- Virtual interaction surface
- Levels-of-precision cursor
- Virtual pad

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**Indirect Touch (Simeone 2016)**
- Touch multi-touch surface to control cursor on primary display
- With second finger touch the surface to select an object under the cursor
- Use surface-based techniques for manipulation
- Choice of absolute or relative mapping
Indirect Metaphors

**Virtual Interaction Surfaces (Ohnishi et al. 2012)**
- Extension of indirect touch
- Mapping of multi-touch surface to nonplanar surfaces in VE
- Allow user to manipulate objects relative to desired paths or other objects
- Supports drawing directly on complex 3D surfaces

**Levels-of-Precision Cursor (Debarba et al. 2012)**
- Extends indirect touch with physical 3D interactions
- Uses smartphone
  - affords multi-touch and 3D interaction using inertial sensors and gyroscopes
- Map smaller area of smartphone to larger area of primary display
- Determine orientation for pointing operations
Indirect Metaphors

Virtual Pad (Andujar and Argelaguet 2007)
- Does not require multi-touch surface
- Virtual surface within the VE is used
- Similar to image plane methods

Indirect Metaphors

Indirect Proxy Techniques
- World in miniature
- Voodoo Dolls
Indirect Metaphors

**World in Miniature (Stoakley et al. 1995)**
- Scale entire world down and bring within user’s reach
- Miniature hand held model of the VE (exact copy)
- Manipulating object in WIM indirectly manipulates object in the VE
- Many design decisions for implementation
  - has scaling issues

**Voodoo Dolls (Pierce et al. 1999)**
- Builds upon WIM and image plane techniques
- Seamless switching between different reference frames for manipulation
  - manipulate objects indirectly using temporary handheld copies of objects (dolls)
  - user can decide which objects to manipulate by using image plane selection (no scaling issues)
- Two handed technique
  - non-dominant hand represents a stationary reference frame
  - dominant hand defines position and orientation of object relative to stationary reference frame
  - user can pass doll from one hand to the other
Indirect Metaphors

Indirect Widget Techniques
- 3D widgets
- Virtual sphere
- Arcball

Bimanual Metaphors
- Dominant and non-dominant hands
- Symmetric vs. asymmetric
- Synchronous vs. asynchronous
- Ex: balloon selection is asymmetric (two hands have different functions) and synchronous (two hands operate at the same time)
Bimanual Metaphors

Symmetric Bimanual Techniques

- Spindle
- iSith

Spindle (Mapes and Moshell 1995)

- Two 6 DOF controllers used to define a virtual spindle that extends from one controller to another
  - center of spindle represents primary point of interaction
- Translation – move both hands in unison
- Rotation – yaw and roll by rotating hands relative to each other
- Scale – lengthen or shorten distance of hands
Bimanual Metaphors

iSith (Wyss et al. 2006)
- Intersection-based Spatial Interaction for Two Hands
- Two 6 DOF controllers define two separate rays
  - ray-casting with both hands
  - shortest line between two rays is found by crossing two vectors to find vector perpendicular to both
  - known as projected intersection point (point of interaction)

Asymmetric Bimanual Techniques
- Spindle + Wheel
- Flexible pointer
### Bimanual Metaphors

#### Spindle + Wheel (Cho and Wartell 2015)
- Extended Spindle to include rotating pitch of virtual object
- Uses virtual wheel collocated with dominant hand cursor
  - twist dominant hand for rotation

#### Flexible Pointer (Olwal and Feiner 2003)
- Make use of two handed pointing
- Curved ray that can point at partially occluded objects
  - implemented as quadratic Bezier spline
Hybrid Metaphors

- Aggregation of techniques
- Integration of techniques
  - HOMER
  - Scaled-world grab

**HOMER (Bowman and Hodges 1997)**
- Hand-centered Object Manipulation
- Extended Ray-Casting
- Select object using ray casting
- Users hand then attaches to the object
- User can then manipulate object (position and orientation) with virtual hand
Hybrid Metaphors

**Scaled World Grab (Mine et al. 1997)**
- User selects object with given selection technique
- Entire VE is scaled down around user’s virtual viewpoint
- Scaling is done so object is within user’s reach
- If center of scaling point is midway between user’s eyes, the user will be unaware of the scaling

Other Aspects of 3D Manipulation

**Nonisomorphic 3D rotation**
- Amplifying 3D rotations to increase range and decrease clutching
- Slowing down rotation to increase precision
- Absolute vs. relative mappings
  - Absolute mappings can violate *directional compliance*
  - Relative mappings do not preserve *nulling compliance*
Isomorphic vs. Non-Isomorphic Philosophies

- Human-Machine interaction
  - input device
  - display device
  - transfer function (control to display mapping)
- Isomorphic – one-to-one mapping
- Non-isomorphic – scaled linear/non-linear mapping

Non-Isomorphic 3D Spatial Rotation

- Important advantages
  - manual control constrained by human anatomy
  - more effective use of limited tracking range (i.e. vision-based tracking)
  - additional tools for fine tuning interaction techniques
- Questions
  - faster?
  - more accurate?
Rotational Space

- Rotations in 3D space are a little tricky
  - do not follow laws of Euclidian geometry
- Space of rotations is not a vector space
- Represented as a closed and curved surface
  - 4D sphere or manifold
- Quaternions provide a tool for describing this surface

Quaternions

- Four-dimensional vector \((v, w)\) where \(v\) is a 3D vector and \(w\) is a real number
- A quaternion of unit length can be used to represent a single rotation about a unit axis \(\hat{u}\) and angle \(\theta\) as
  \[
  q = (\sin\left(\frac{\theta}{2}\right) \hat{u}, \cos\left(\frac{\theta}{2}\right)) = e^{\frac{\theta}{2} \hat{u}}
  \]
Linear 0\textsuperscript{th} Order 3D Rotation

- Let $q_c$ be the orientation of the input device and $q_d$ be the displayed orientation then

\begin{align*}
(1) \quad q_c &= (\sin(\frac{\theta}{2}) \hat{u}_x, \cos(\frac{\theta}{2})) = e^{\frac{\theta}{2} \hat{u}_x} \\
(2) \quad q_d &= (\sin(\frac{k\theta}{2}) \hat{u}_x, \cos(\frac{k\theta}{2})) = e^{\frac{k\theta}{2} \hat{u}_x} = q_d^k
\end{align*}

- Final equations w.r.t. identity or reference orientation $q_o$ are

\begin{align*}
(3) \quad q_q &= q_c^k \\
(4) \quad q_d &= (q_c q_o^{-1})^k q_o, \quad k = \text{CD gain coefficient}
\end{align*}

Non-Linear 0\textsuperscript{th} Order 3D Rotation

- Consider

\begin{align*}
(3) \quad q_d &= q_c^k \\
(4) \quad q_d &= (q_c q_o^{-1})^k q_o
\end{align*}

- Let $k$ be a non-linear function as in $\omega = 2 \arccos(q_c \cdot q_o)$ or $\omega = 2 \arccos(w)$

\[ k = F(\omega) = \begin{cases} 
1 & \text{if } \omega < \omega_o \\
1 + c(\omega - \omega_o)^2 & \text{otherwise}
\end{cases} \]

where $c$ is a coefficient and $\omega_o$ is the threshold angle.
Design Considerations

- **Absolute mapping** – taken on \(i\)-th cycle of the simulation loop
  \[ q_{d_i} = q_{c_i}^k \]

- **Relative mapping** – taken between the \(i\)-th and \(i-1\)th cycle of the simulation loop
  \[ q_{d_i} = (q_{c_i} q_{c_{i-1}}^{-1})^k q_{d_{i-1}} \]

Absolute Non-Isomorphic Mapping

- Generally do not preserve directional compliance
- Strictly preserves nulling compliance
Relative Non-Isomorphic Mapping

- Always maintain directional compliance
- Do not generally preserve nulling compliance

Amplified Non-Linear Rotation for VE Navigation (1)

- Users expect the virtual world to exist in any direction
  - 3-walled Cave does not allow this
  - adapt expected UI to work in restricted environment
- Amplified rotation allows users to see a full 360 degrees in a 3-walled display
- A number of approaches were tested
  - important to take cybersickness into account
Amplified Non-Linear Rotation for VE Navigation (2)

- Apply a non-linear mapping function to the user’s waist orientation $\theta$ and his or her distance $d$ from the back of the Cave
- Calculate the rotation factor using a scaled 2D Gaussian function

$$
\phi = f(\theta, d) = \frac{1}{\sqrt{2\pi \sigma_1}} e^{-\frac{(|\theta|-\pi(1-d/L))^2}{2\sigma_2^2}}
$$

- The new viewing angle is $\theta_{new} = \theta (1 - \phi)$

Amplified Non-Linear Rotation for VE Navigation (3)

$$
\sigma_1 = 0.57 \\
\sigma_2 = 0.85 \\
L = 30 \\
\mu = \pi
$$
Non-Linear Translation for VE Navigation (1)

- Users lean about the waist to move small to medium distances
  - users can lean and look in different directions
- Users can also lean to translate a floor-based interactive world in miniature (WIM)
  - Step WIM must be active
  - user’s gaze must be 25 degrees below horizontal

Non-Linear Translation for VE Navigation (2)

- Leaning vector $\vec{L}_R$ is the projection of the vector between the waist and the head onto the floor
  - gives direction and raw magnitude components
- Navigation speed is dependent on the user’s physical location
  - Leaning sensitivity increases close to a boundary
- Linear function - $L_T = a \cdot D_{\text{min}} + b$
- Mapped velocity - $v = \vec{L}_R - L_T$
Non-Linear Translation for VE Navigation (3)

- Navigation speed is also dependent on the user’s head orientation with respect to the vertical axis
  - especially useful when translating the floor-based WIM
- Mapping is done with a scaled exponential function
  \[ F = \alpha \cdot e^{-\beta |\vec{H} \cdot \vec{v}_{up}|} \]
- Final leaning velocity is
  \[ v_{final} = F \cdot \vec{v} \]

Other Aspects of 3D Manipulation

**Multiple Object Selection**
- Serial selection mode
- Volume-based selection techniques
  - e.g., flashlight, aperture, sphere-casting
- Defining selection volumes
  - e.g., two-corners, lasso on image plane
- Selection-volume widget
  - e.g., PORT
Other Aspects of 3D Manipulation

Progressive Refinement
- Gradually reducing set of objects till only one remains
- Multiple fast selections with low precision requirements
- SQUAD
- Expand
- Double Bubble

SQUAD (Kopper et al. 2011)
- Sphere-casting refined by QUAD menu
  - progressive refinement for dense VEs
- User specifies initial subset of environment using sphere cast
- Selectable objects laid out in QUAD menu
- Use ray-casting to select one of the four quadrants
  - selected quadrant is laid out in four quadrants
  - repeat until one object is selected
Other Aspects of 3D Manipulation

**Expand (Cashion et al. 2012)**
- Similar to SQUAD
- User selects collection of objects
- User’s view expands this area and creates clones of the selectable objects (laid out in grid)
- User uses ray-cast to select object

**Double Bubble (Bacim 2015)**
- Both SQUAD and Expand suffer from initial selection containing large set of objects
- 3D bubble cursor is used upon initial selection
  - bubble not allowed to shrink beyond a certain size
- Objects laid out in a menu and selected using 3D bubble cursor
Design Guidelines

- Use existing manipulation techniques unless a large amount of benefit might be derived from designing a new application-specific technique.
- Use task analysis when choosing a 3D manipulation technique.
- Match the interaction technique to the device.
- Use techniques that can help to reduce clutching.

- Nonisomorphic ("magic") techniques are useful and intuitive.
- Use pointing techniques for selection and grasping techniques for manipulation.
- Consider the use of grasp-sensitive object selection.
- Reduce degrees of freedom when possible.
- Consider the trade-off between technique design and environment design.
- There is no single best manipulation technique.
Case Studies

**VR Gaming Case Study**
- Bimanual approach:
  - Non-dominant hand defines interaction area ("flashlight")
  - Dominant hand selects/manipulates in that area ("tool")
- Playful metaphors, multiple tools
- Key concepts:
  - Progressive refinement selection techniques can help users avoid fatigue by not requiring precise interactions.
  - Basic 3D selection and manipulation techniques can be customized to fit the theme or story of a particular application.

**Mobile AR Case Study**
- Finger-based selection for infrequent use with single datasets
- Pen-based selection for frequent use or richer datasets
- Key concepts:
  - Size of selectable items: keep the size of your selectable objects or menu items as small as possible, while reflecting the limitations of your input method and the visibility (legibility) of these items.
  - Selection method: depending on the frequency of selection tasks, different input methods could be preferable. Often, there is a direct relationship between input method, selection performance and frequency, and user comfort.
Conclusion

- 3D manipulation is a foundational task in 3D UIs
- Huge design space with many competing considerations
- Consider tradeoffs in your application context carefully

Next Class

- Navigation – Travel
- Readings
  - 3DUI Book – Chapter 7