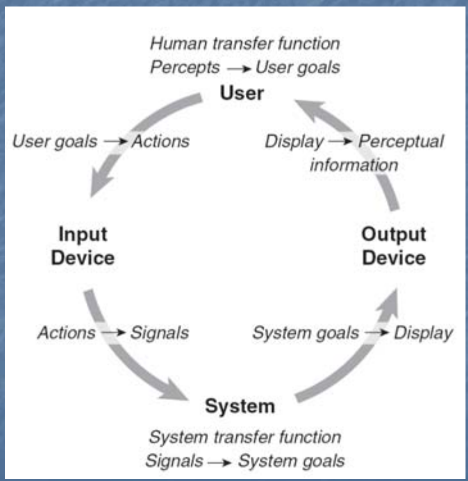
3D User Interface Techniques for Selection and Manipulation

Lecture #9: Selection and Manipulation
Spring 2025
Joseph J. LaViola Jr.

Interaction Workflow



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)

3D Manipulation Tasks

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

Task	Parameters
Selection	Distance and direction to target, target size, density of objects around the target, number of targets to be selected, target occlusion
Positioning	Distance and direction to initial position, distance and direction to target position, translation distance, required precision of positioning
Rotation	Distance to target, initial orientation, final orientation, amount of rotation, required precision of rotation

3D Manipulation Tasks

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

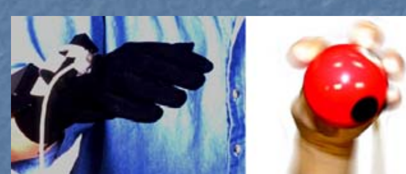
Manipulation Techniques and Input Devices

- 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

3D Manipulation Tasks

Manipulation Techniques and Input Devices

- Device shape
  - Generic vs. task-specific
- Device placement/grasp
  - Power grip
  - Precision grip
    - Use fingers
    - Reduce clutching



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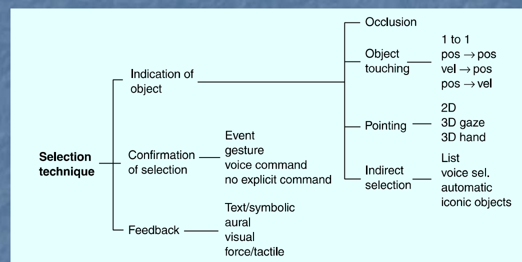
Classifications for 3D Manipulation

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



Grasping Metaphors

Hand-Based Grasping

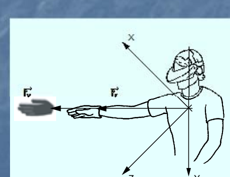
- Simple virtual hand
- Go-Go

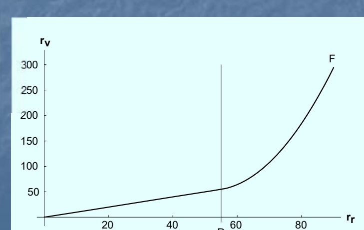
$$r_v = F(r_r) = \begin{cases} r_r & \text{if } r_r \le D \\ r_r + \alpha(r_r - D)^2 & \text{otherwise} \end{cases}$$

where r_r = length of $\overrightarrow{\boldsymbol{R}_r}$

r_v = length of $\overrightarrow{\boldsymbol{R}_v}$

D, α are constants

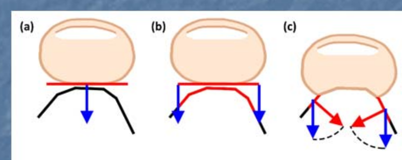




Grasping Metaphors

Finger-Based Grasping

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



Grasping Metaphors

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

Grasping Metaphors

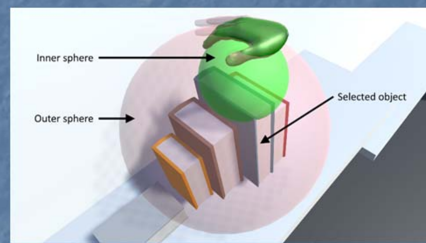
God Fingers (Talvas et al. 2013)

- 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



Grasping Metaphors

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

Grasping Metaphors

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

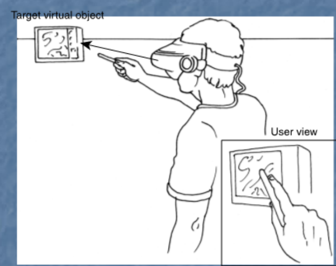
Pointing Metaphors

- 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



Pointing Metaphors

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)

Pointing Metaphors

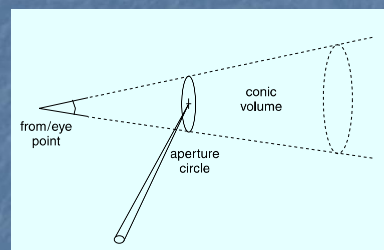
Image Plane Pointing (Pierce et al. 1997)

- 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



Pointing Metaphors

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

Pointing Metaphors

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

Pointing Metaphors

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

Pointing Metaphors

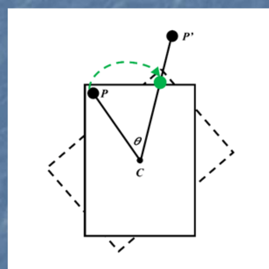
Absolute and Relative Mapping (Kopper et al. 2010)

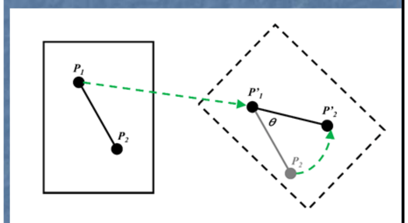
- Useful in dense environments
- Provides manual control of control to display gain ratio of pointing
  - lets users increase the effective angular width of targets
- Can give user impression of slow motion pointer

Surface Metaphors

Surface-Based 2D Interaction Techniques

- Dragging
- Rotating

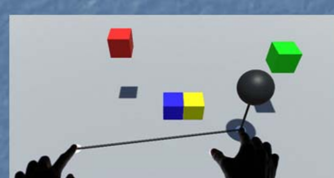


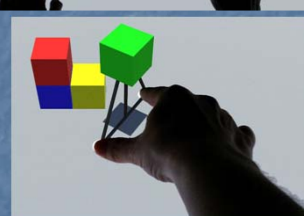


Surface Metaphors

Surface-based 3D Interaction Techniques

- Pinching
- Void shadows
- Balloon selection
- Corkscrew widget
- Triangle cursor

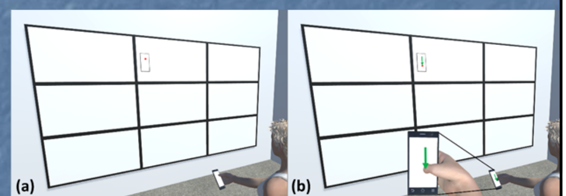




Indirect Metaphors

Indirect Control-Space Techniques

- Indirect touch
- Virtual interaction surface
- Levels-of-precision cursor
- Virtual pad



Indirect Metaphors

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

Indirect Metaphors

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

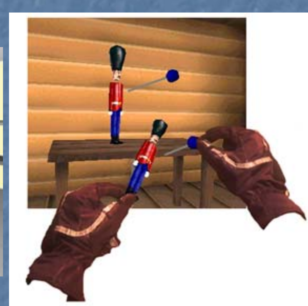
Virtual Pad (Andujar and Argelaguet 2007)

- 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

Indirect Metaphors

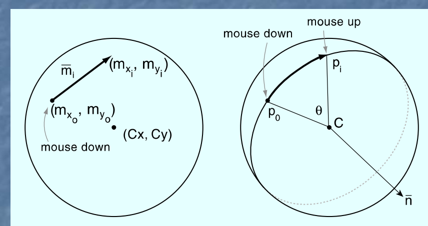
Voodoo Dolls (Pierce et al. 1999)

- 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



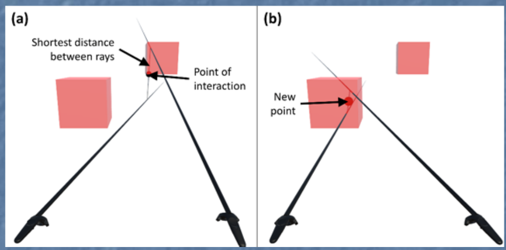
Bimanual Metaphors

- 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



Bimanual Metaphors

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

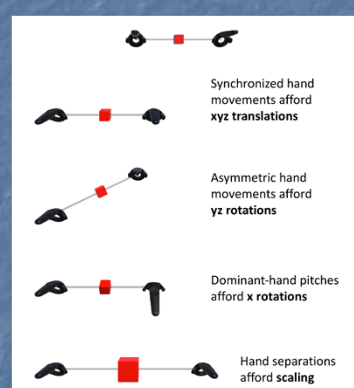
iSith (Wyss et al. 2006)

- 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)

Bimanual Metaphors

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

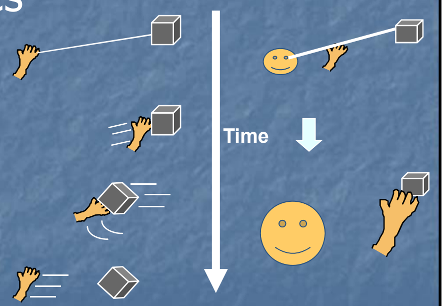
Bimanual Metaphors

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



Hybrid Metaphors

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

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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 θ as

$$q = (\sin(\frac{\theta}{2}\hat{u}), \cos(\frac{\theta}{2})) = e^{\frac{\theta}{2}\hat{u}}$$

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Linear 0th Order 3D Rotation

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

$$(1) \quad q_c = (\sin(\frac{\theta_c}{2}\hat{u}_c), \cos(\frac{\theta_c}{2})) = e^{\frac{\theta_c}{2}\hat{u}_c}$$

$$(2) \quad q_d = (\sin(\frac{k\theta_c}{2}\hat{u}_c), \cos(\frac{k\theta_c}{2})) = e^{\frac{k\theta_c}{2}\hat{u}_c} = q_c^k$$

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

$$(3) \quad q_q = q_c^k \qquad (4) \quad q_d = (q_c q_o^{-1})^k q_o, \; k = \text{CD gain coefficient}$$

Non-Linear 0th Order 3D Rotation

- Consider

$$(3) \quad q_d = q_c^k \qquad (4) \quad q_d = (q_c q_o^{-1})^k q_o$$

- Let *k be* a non-linear function as in

$$\omega = 2\arccos(q_c \cdot q_o) \text{ or } \omega = 2\arccos(w)$$

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

where c is a coefficient and ω_o is the theshold 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-1th* 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

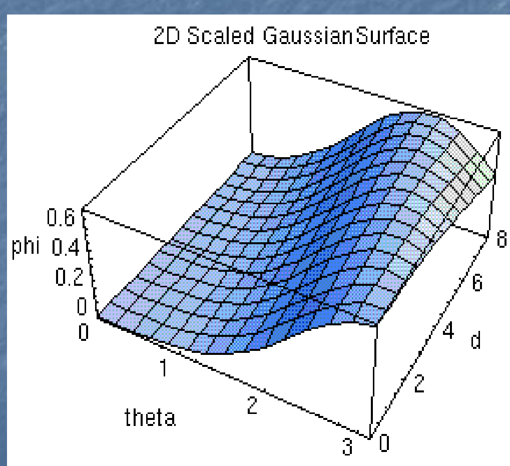
Amplified Non-Linear Rotation for VE Navigation (2)

- Apply a non-linear mapping function to the user's waist orientation θ 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 - $L_T = a \cdot D_{\min} + b$
- Mapped velocity - $v = \left\| \vec{L}_R \right\| - L_T$

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

$$F = \alpha \cdot e^{-\beta \left| \vec{H} \cdot \vec{V}_{up} \right|}$$

- Final leaning velocity is $v_{final} = F \cdot v$

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

Other Aspects of 3D Manipulation

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

Other Aspects of 3D Manipulation

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.

Design Guidelines

- 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.

Case Studies

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