Survey and Classification of Spatial Object Manipulation Techniques

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Abstract

This paper outlines a classification scheme for spatial object manipulation techniques based on naturalness, range of interaction space, degrees of freedom, and atomic actions. Design implications of each category are discussed. Subsequently, a number of current 3D input devices are reviewed in light of the proposed classification scheme and some general conclusions are drawn highlighting some of the limitations of current 3D input devices.

1. Introduction

The rapid pace of technological advances in computing power, display development, and interface design enables the creation of computer models and simulations of increasing complexity. As three-dimensional (3D) computer-generated visualizations are being used more widely in areas such as medicine, financial data visualization, product design, and architecture, the search for usable input devices for manipulating 3D objects becomes of greater relevance to many disciplines. In the traditional two-dimensional (2D) graphical user interface (GUI), the computer mouse established itself early as the de facto standard 2D input device. As yet, there is no such clear winner for 3D interfaces, and there may never be. Indeed, most of the 3D interfaces designed to date can be characterized by a trend of *divergence* to special-purpose, application specific interfaces and devices. Difficulties in establishing a standard 3D input device include

- the engineering challenges in terms of sensor technologies,
- limited knowledge of the most effective ways for humans to interact with synthetic 3D environments, and
- application and task-specific demands and constraints.

There has been a considerable research and development effort in recent years aimed at 3D interaction and user interfaces. An impressive number of papers are available that provide information on this topic. In a recent survey paper, Hand [1] provides an overview of the state of the art in 3D interaction techniques, but does not discuss input devices themselves in any great depth. Shumin Zhai [2], in a special issue on 'Interaction in 3D Graphics' of the SIGGRAPH Computer Graphics Newsletter, provides an excellent practical comparison of some 6DOF input devices based on aspects of their usability. Wuthrich [3] presents new insights into the theoretical aspects of 3D interface design from the system theory point of view. An up-to-date annotated bibliography of 3D user interface papers is available online [4].

This paper is not intended as a comprehensive literature review of 3D interaction. Rather, it is our aim to provide an overview of the latest developments in 3D input for spatial interaction, based on a number of relevant characteristics that provide a framework for classification. The remainder of this paper is organized as follows: Section 2 presents the general characteristics we have identified as important in classifying the interaction devices, namely naturalness, range of interaction supported, degrees of freedom supported, and type of action supported. Section 3 then discusses a number of recently introduced interaction devices in terms of the classification scheme presented in section 2.

2. Classification Scheme

2.1 Naturalness

Perhaps the most important hint in designing 3D interfaces can be derived from observations of how we interact with the real world. By the time we reach adulthood we have perfected many manipulation and navigation skills to the point where we can perform many tasks without conscious attention. The interface becomes invisible. It is this level of naturalness and transparency that one aims to achieve in interacting with computers. When done well, the interaction shouldn't feel like a human-computer interaction anymore, but rather like a human-product or human-task interaction. The focus should be on interacting *through* a computer instead of interacting *with* a computer.

One approach that has been used to design interfaces that feel natural is known as the *ecological approach*, and owes much to the thinking of James Gibson [5][6]. The term 'ecological' refers to the emphasis this theory places on the relationship between the individual and his or her environment. From this perspective, the combined characteristics of the environment and the individual define what is possible for the individual within the environment. In Gibson's terminology, the environment is perceived by the individual as a set of *affordances*, i.e. 'the actions a given environment affords to a given acting observer'. Thus, in the ecological approach, perception and action are tightly interlocked and mutually constraining phenomena. This view has important implications for design [7][8][9]. First of all, the tight coupling of perception and action suggests that interfaces providing a unified perception-action space may be very effective for direct spatial manipulation of objects. Several systems have applied this principle in interface design. For example, in the system designed by Schmandt [10], a 3D scene is projected stereoscopically onto a half silvered mirror placed at an angle of 45 deg. The user can then reach underneath the mirror into the 3D scene and manipulate it using a wand. Variations on this system include the ReachIn system [11], which uses the SensAble Phantom (discussed later) as a force feedback manipulation device. Other examples of systems with a unified perception-action space include graspable user interfaces [12][13], and the Cubby system [14].

A second implication that can be derived from the ecological approach is that one needs to provide the appropriate affordances to the user. The reciprocity between the individual and the environment implies that interface design needs to be tailored to a specific kind of encounter between the user and the system rather than use generic anthropometric standards that apply across a range of behavioral settings. A good example of such a special purpose system is the VR CAD system developed at Delft University of Technology [9], which provides the designer with virtual design tools such as a tong, a brush, a stapler, and a pair of scissors, which afford the appropriate actions. For example, 3D objects can be linked using a stapler, rescaled using a tong, and unlinked using scissors. Thus, these tools afford the behavior for which they were designed in the real world, although they can also offer new functions to users should they so desire.

2.2 Range of Spatial Interaction

In general, the space that surrounds the user can be meaningfully segmented into several ranges, based on principles of human perception and action. Cutting and Vishton [15] divided the spatial layout surrounding the perceiver into three egocentric regions that grade into one another: personal space, action space and vista space. *Personal space* refers to the zone that falls within arm's reach of the observer, thus having a diameter of around 2 meters. Beyond the range of personal space, *action space* refers to the space of an individual's public actions. Within this space we can move quickly, speak easily and toss or throw objects. Cutting and Vishton [15] suggest this space is limited to about 30m on the basis of the decline in effectivity of disparity and motion perspective as cues to spatial layout. Beyond this range, *vista space* stretches out until the visual horizon. Although the vast majority of interaction devices operate within the range of personal space, it is interesting to note that visual display devices have the capability of visualizing virtual objects at all possible ranges, thereby introducing the need for variable mappings of input devices (e.g. a mouse) to their visual counterparts (e.g. a pointer on the screen), or the use of interaction styles that do not rely on spatial mappings, such as speech. When following the design principle that perception and action space should ideally coincide, this limits the range at which interaction objects can be visualized.

A slightly different segmentation of interaction space has been proposed by Stappers et al. [16]. Based on the Gibsonian perception-action coupling paradigm, they partition body-scaled space in three ranges: small, middle and large. In the small range we can perform detailed manipulations using our fingers and hands, and receive feedback through detailed vision and haptics. In the middle range we can use our hands, arms and posture to grasp objects and make gestures. The large range is out of reach and is used mainly provide an overview and a feeling of presence in the environment [16].

Interaction devices operate on a variety of spatial scales, and can thus be meaningfully classified according to the range of interaction supported by a particular device. As was discussed, each range has its own characteristics in terms of perceptual-motor requirements, supported task and technological constraints. Based on the volume of the interaction space the devices can be classified as

- Tablet-size interaction devices: Tablet-size devices have a limited manipulating space, which supports detailed movements. Typically these devices have an interaction space equivalent to that of finger and wrist movements. Most of the interaction tools developed belong to this category, such as the mouse, an LCD tablet or the Cubby system [14].
- Tabletop-size interaction devices: Tabletop-size devices have a larger interaction space, roughly within arm's reach. Devices belonging to this category include the Videodesk [18] and the Build-It system [13].
- Room-size interaction devices: These interaction devices can have an entire room as the interaction space. The user can either use the space as an ambient context [18] or actively interact with it through various tracking devices and computer vision technologies. Effective interaction styles can include speech or gesture. Examples of such systems are smart rooms [20] or the CAVE [21].

2.3 Degrees of freedom

To uniquely specify any point in three-dimensional space one requires at least 3 independent coordinate positions, say (x, y, z). However, many 3D manipulation tasks require the user to manipulate entire objects rather than points. If these objects are rigid and have a specific regular shape (e.g., cube, cylinder, etc), one can specify movements of this object by three translational (x, y, z) and three rotational movements (θ, ϕ, φ - along the x, y, and *z-axis* respectively). Thus, to be able to manipulate 3D objects, one generally needs 6 degrees of freedom (6 DOF). As a general rule, the degrees of freedom of the task should match the degrees of freedom of the interaction device. When the task has more degrees of freedom than the interaction device, the user interface will need to support a complex dialogue of composed interactions, rather than direct manipulation. The converse can also be inefficient, since in such a case the input device is not physically constrained to the same degrees of freedom as the task [22].

Based on the number of degrees of freedom incorporated, interaction devices can be classified as

- 1 DOF: for example a slider or dial used to control one parameter, such as volume
- 2 DOF: a standard mouse has 2 DOF and enables tasks such as selecting or drawing in 2D space
- More than 2 DOF but less than 6 DOF: For 3D interaction more than 2 DOF is required. Several modifications to the mouse were made to incorporate greater degrees of freedom. But most of these devices (like the Bat, Rockin' Mouse etc.) have less than 6 DOF. These devices are usually meant for specific applications that do not require 6 DOF.
- 6 DOF: these input devices, such as the flying mice, and can easily provide the basic 3D motions like translation and rotation.
- More than 6 DOF: most of the devices in the previous categories are meant for single-handed use. But real world observations reveal that we prefer to perform operations with both our hands. Driven by this motivation many two-handed interaction devices are being introduced. These devices can provide up to 12 DOF. Several devices have been developed which provide varying DOF between 6 and 12. Motion tracking devices for animation purposes (e.g. body suits) can have an even larger number of DOFs (i.e. 100+).

The above classification has been based on input devices alone. One may also include the output/visualization part in the classification as well. The manipulation device would then represent a region or a point in a three dimensional space. The three dimensions being

- The degrees of freedom at input,
- The degrees of freedom at output, which includes degrees of freedom for 3D visualization (3 DOF), speech/ audio, force feedback etc.
- Separability or integrability of the input and the output devices [23]. This would signify to what extent action and perception space would coincide, as discussed in 2.1.

2.4 Type of action

Every specific application domain has certain tasks that need to be performed. Tasks can be common to different application domains. A task in itself is a coordinated or logical performance of actions. For any application domain we can draw an application-task-action hierarchy tree as in Figure 1.

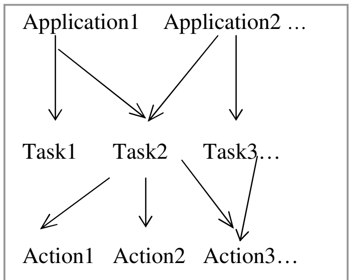

Figure 1. Application-Task-Action Hierarchy

There are several kinds of elementary actions. Wuthrich [3] introduced a classification based on the number of elementary or atomic actions that can be performed. These can be reduced to the following three:

- Selection/Grabbing:
  The action of grabbing secures a firm interaction with surrounding objects for comfortable manipulation.
- Positioning:
  Displacing objects by movements from one position to another, whilst retaining the object's shape and size.
- Deforming:
  This action enables modification of the shape and size of the objects.

While it is possible to change the shape of an object by selecting a point within the object and repositioning that point, we regard this to be a composite of two atomic actions (selecting and positioning) rather then the atomic action of deforming. In our view, deforming takes place when an input device enables direct manipulation of the object shape, for instance through molding it, as in the cube-based shape deformation interface

This set of basic atomic operations is only for object manipulation and it should be kept in mind that some operations like zooming are view manipulations rather than object manipulations, thus falling under a different classification scheme.

3. Overview of Current 3D Object Manipulation Schemes

3.1 Phantom

The Phantom, developed by SensAble Technologies Inc [24], is a 6 DOF input device which also provides force feedback (only 3 DOF). The mechanical motors and pulleys detect the position of a stylus. The strength of the Phantom is in its ability to provide 3D touch capabilities, thus making it good as a

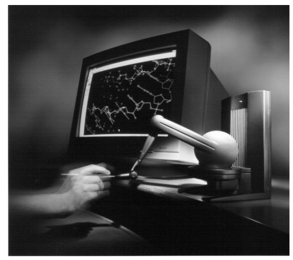

Figure 2. The Phantom

haptic interface. The Phantom is being used in many 3D CAD/CAM and medical applications. Different types of Phantom can support different interaction ranges, from tablet-size to tabletop-size. The basic atomic operations that are best supported by the Phantom are selecting and positioning. As mentioned earlier, the Phantom has been integrated into the ReachIn system which offers a unified perception-action space.

3.2 Bat

Ware investigated interaction techniques for a six degree-of-freedom magnetic tracker, which he refers to as "the Bat" [25][26]. The Bat can be used as a relative positioning device, i.e. a button on the Bat acts as a clutch allowing or disallowing movement, enabling users to employ a "ratcheting" technique to perform large translations or rotations. The Bat is a 6 DOF input device, it can be used for positioning and selecting actions. The range of interaction is limited to tablet-size manipulations.

3.3 Laser Pointer Pro

The Laser Pointer Pro [27] replaces the cursor as an interaction device. A beam is cast from the user's pointer in a straight line. The first object to be intersected by the ray is selected for further manipulation. This has the advantage that it allows "action at a distance" (AAAD). The user does not need to be close to the object in order to manipulate it. The Laser Pointer was first introduced for the Mac operating system but is now available for many other operating systems. The Laser Pointer could be used for any range of interaction, though it would be well suited for room-size interactions. The basic atomic operations that can be performed are selecting/ grabbing and positioning operations. The device has only two degrees of freedom for positioning, while it has 3 DOF for selecting.

3.4 JDCAD

JDCAD [28] is a solid modeling system, which is operated using a Bat, and uses a cone-shaped selection volume rather than a simple line (as used in Laser Pointer Pro) to overcome problems associated with selecting small objects. By switching modes, the Bat can be used to interactively rotate and move the model under construction, select objects for subsequent operations or orient and align individual pieces of the model. The atomic actions and range of interaction supported is the same as with the Bat.

3.5 Rockin' Mouse

The Rockin' Mouse introduced by Balakrishnan et al [29] retains the characteristics of the mouse while providing a curved base allowing the mouse to be tilted in 2 directions. The amount of tilt can be perceived and provides 2 extra degrees of freedom over the conventional mouse. The

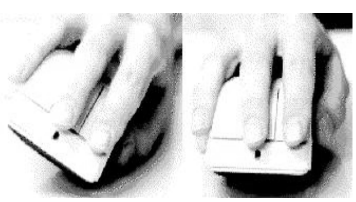

Figure 3: Rockin' Mouse

prototype implementation works on a Wacom digitizing tablet [30]. The authors were able to demonstrate that the Rockin' Mouse can provide at least a 30% performance gain over the regular mouse for 3D positioning tasks**.** On the other hand, since a muscle group that is different from those of the x-y mouse motion operates the depth dimension, it can be difficult to produce precise, simultaneous, co-ordinated motion using the Rockin' Mouse [2]. The interaction space of this device is limited to tablet-size manipulations. The atomic actions are selection and positioning.

3.6 3-Draw

Sachs' 3-Draw system [31] is a computer-aided design tool that facilitates the sketching of 3D curves. In 3-Draw, the user holds a stylus (6 DOF) in one hand and a tablet (6 DOF) in the other. These tools serve to draw and view a 3D virtual object, which is seen on a desktop monitor. The palette is used to view the object, while motion of the stylus relative to the palette is used to draw and edit the curves making up the object. The 3-Draw system enables two-handed tablet-size interactions for selecting and positioning object. Sachs notes that "users require far less concentration to manipulate objects relative to each other than if one object were fixed absolutely in space while a single input sensor controlled the other".

3.7 Cube based input device for 3D shape deformation

Murakami and others [32] propose an interface where a cube is the basic and general control volume shape for 3D shape deformation. The shape deformations are measured using electrically conductive elastic polyurethane foams. The interface provides a direct and intuitive way of manipulating a 3D shape modeled and displayed on the computer screen. The user can deform the control volume and objective shape displayed on the screen by pressing, bending, and twisting the input device cube with the bare hands. The

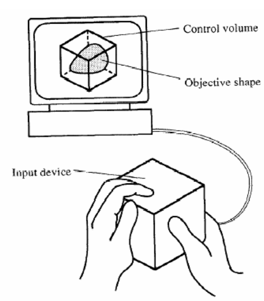

Figure 4: Concept of the shape deformation interface

authors explain that although the interface is intuitive, it is only useful for designing basic shapes. The shape data need to be transferred to a 3D CAD system for finishing. This 2-handed interface can be used for performing a deformation style atomic action. The range of interaction is limited to tablet-size and can potentially have up to 6 DOF.

3.8 Frog

The Frog [33] is a small 6 DOF, magnetic tracker, similar to the Bat, that measures location and orientation. The Frog is symmetrical and can be used comfortably by both hands. The device has been used as a 2-handed interaction device for CAD modeling. A complaint of the subjects in the experiments is that the wire hindered in the free operation of the device (p. 187).

3.9 Passive Interface Props

Hinckley et al [34] proposed a two-handed interaction device for neurosurgical visualization using several props. The surgeon is provided with a head prop, a small rubber

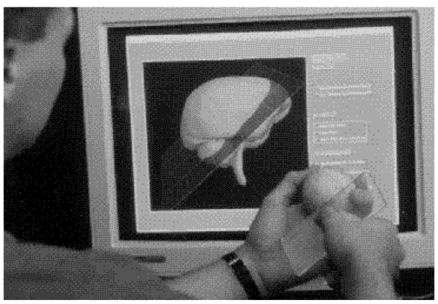

Figure 5. A user Selecting with the interface Prop

sphere which corresponds to the patient's inter-hemispheric fissure, for manipulating the individual patients data (like zooming, rotation etc), a cutting plane prop for specifying the position and orientation of an arbitrary slice through the patients anatomy, and a trajectory selection prop, which allows to specify 3D vectors and points. The interface provides 3D interaction but evaluations showed that the user felt a distance between the interaction and the visualization. This interface can be used for tablet-size interactions and for the atomic actions of selection and positioning.

3.10 Image plane interaction techniques in 3D immersive environments

This technique [35] is based on the 1980's comedy show "The Kids in the Hall" and operates on 3D objects at a distance by interacting with their 2D projections on the image plane. The idea is of using the position of the users hand relative to the image plane and using that point as a 2D cursor for selecting objects from the scene. Several metaphors are used like Head Crusher, Sticky Finger, Lifting Palm, Framing Hands etc. This interaction style is suited for tabletop and room-size interaction spaces and can support all the atomic actions. It supports at least 4 degrees of freedom.

3.11 Cubic Mouse

The Cubic Mouse [36] consists of a cube shaped case with three rods and control buttons. The rods are approximately orthogonal and represent the axes of a co-ordinate system. The device has a tracker embedded which can enable users to intuitively specify three-dimensional co-ordinates in graphics applications, where it is necessary to view slices of volumetric data. This two-handed interaction device has 6 DOF. The interaction space is limited to tablet and tabletop-size. The atomic operations that

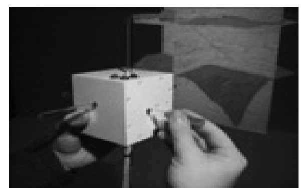

Figure 6. The Cubic Mouse

can be performed is positioning.

3.12 Chameleon

The Chameleon [37], developed at the University of Toronto, consists of a high-fidelity monitor palm computer which makes the user spatially aware of their location and orientation in an information space, by integrating the 3D input controller and output display. A response button and a 6D input device are attached to the small monitor. The user can navigate in a 3D-information space using the monitor. The system is modeled after the "eye-in-hand" metaphor. The user can select objects by lining up the cross-hair cursor with the desired object and clicking on the response button. The set of hand movements provide the user with a 3D sensation. However, the users felt they had an object view instead of egocentric view. The interaction space is scalable from tablet-size to room-size depending on the tracking technology used. The prototype Chameleon described in [37] is tethered by cords due to the video feed and 6D input device.

3.13 Personal Interaction Panel

The Personal Interaction Panel or PIP [38] consists of a pad and pen tracked using a Polhemus Fasttrak 6 DOF tracking sensors for interaction and a see-through head-mounted display (HMD), for visualization. The position and orientation tracking of all three parts allows accurate evaluation of the spatial relations for perspective matching of the real and augmented environments. The PIP can be used for multi-person table-size interaction with CAD applications and volume-data browsing. It has a maximum of 6 DOF and can perform selection and positioning operations.

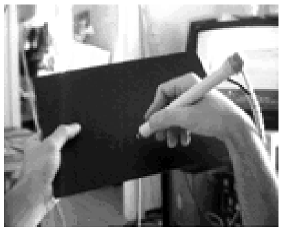

Figure 7. The Personal Interaction Platform

Zsolt [38] signals the need for using wireless technology to seamlessly integrate the PIP into the user's environment.

4. Conclusion

In general, there appears to be a trend towards more natural and intuitive input devices, with an effort towards unifying perception and action space and providing two-handed interaction. It has been argued in [39] that 2 hands do more than just save time over one hand. The users have a keen sense of where their hands are relative to one another and this can help develop interactions which are potentially less demanding of visual attention.

From reviewing the 3D input device literature it is evident that little formal evaluations are available for the different interfaces. Interfaces that perform similar tasks are seldom being compared in terms of performance or usability. However, a number of informal studies have reported that wires hindered effortless interaction, thereby suggesting that incorporating wireless technology into the design of input devices has added value. In addition, most informal studies report a user preference towards devices that support relative positioning (like the Bat) rather than absolute positioning.

Clearly, more user evaluations are needed, especially in the early design stages of the input device, so that prospective users can have a real impact on the final outcome of the design.

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Table 1. Summary of the classification of the spatial input devices.

Device	DOF@Input	Action-Perception Space	Range of Interaction	Actions Performed	KEY
Phantom	6	0 (1 for ReachIn system)	Tb, Tt	S, P	**Separability:** 0 - Separated 1 - Integrated **Range of Interaction:** Tb - Tablet Size Tt - Table Size Rs - Room Size **Actions Performed:** S - Selection P - Positioning D - Deforming
Bat	6	0	Tb	S, P	
Laser Pointer Pro	2	0	Rs	S, P	
JDCAD	Same as for the Bat				
Rockin' Mouse	4	0	Tb	S, P	
3-Draw	6&6	0	Tb	S, P	
Shape Deformer	6	0	Tb	D	
Frog	6	0	Tb, Tt	S, P	
Image Plane Intersection	4 (at least)	1	Tt, Rs	S, P, D	
Passive Interface Prop	4-Cutting Prop 2-Selecting Prop	0	Tb	S, P	
Cubic Mouse	6	0	Tb, Tt	P	
Chameleon	6	0	Tb, Tt, Rs	S, P	
PIP	6	1	Tb, Tt	S, P	