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A Survey and Taxonomy of 3D Menu Techniques

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Abstract

A huge variety of interaction techniques was developed in the field of virtual and augmented reality. Whereas techniques for object selection, manipulation, travel, and wayfinding were covered in existing taxonomies quite in detail, application control techniques were not sufficiently deliberated yet. However, they are needed by almost every mixed reality application, e.g. for choosing from alternative objects or options. For this purpose a great variety of distinct three-dimensional menu selection techniques is available. This paper surveys existing 3D menus from the corpus of literature and classifies them according to various criteria. The taxonomy introduced here assists developers of interactive 3D applications to better evaluate their options when choosing and implementing a 3D menu technique. Since the taxonomy spans the design space for 3D menu solutions, it also aids researchers in identifying opportunities to improve or create novel virtual menu techniques.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [Information Interfaces and Presentation]: User Interfaces–Interaction styles I.3.6 [Computer Graphics]: Methodology and Techniques–Interaction Techniques I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism–Virtual Reality

1. Introduction

In the past decade much of the research in the field of virtual reality (VR) has been devoted to developing interaction techniques for object selection, manipulation, travel, and wayfinding. In addition to that techniques for application or system control were introduced which allow for changing states, adjusting scalar values, and especially for choosing from alternative objects or options. However, interfaces for system control tasks in virtual environments (VEs) have not been extensively studied [BW01].

Since these tasks are also an integral part of conventional desktop interfaces, well-known 2D desktop interaction techniques were adapted to VEs. This works quite well for a number of 3D state control widgets (e.g. buttons), but causes problems for menu selection techniques. Thus all menu solutions integrating 2D approaches into space have to face problems such as the greater skills required in reaching a menu item in space as well as the lack of tactile feedback [Han97]. Therefore a great variety of distinct three-dimensional solutions was proposed for virtual environments (refer to the early work by Jacoby and Ellis [JE92] for an introduction to virtual menus). As Kim et al. postulate in [KKP*00], menus show enough idiosyncrasies that warrant a more in depth look as a generic task of its own (compared to manipulation and selection). Hence it is worth studying existing solutions and developing a perspective on their design and use.

Still, application developers cannot rely on an established set of 3D menu techniques being at their hand for implementing an interactive 3D application. There is no repertory of menu solutions available comparable to 2D user interface development. Applications are often developed from scratch, especially in the even younger research areas of augmented reality (AR) and desktop VR. For these promising fields even less menu solutions are available. Moreover, to our knowledge there exists neither a survey nor a unifying taxonomy of application control and especially menu techniques in these fields. This makes it difficult for developers to choose a suitable menu technique for their VE applications.

This work attempts to close this gap and to provide a comprehensive survey of 3D menu solutions for all areas of the mixed reality continuum including the field of desktop virtual environments. In addition, solutions shall be classified in a taxonomy facilitating VE application developers the comparison and choice of appropriate menu solutions. Since the taxonomy spans the design space for 3D menu solutions, it also allows to identify opportunities for improving or creating novel virtual menu techniques. 3D menus should also be an integral part of 3D user interfaces realizing alternatives to present desktop interfaces.

The paper is structured as follows. The next section discusses previous work related to classification and taxonomy approaches in the field of 3D menus. In section 3 existing menu techniques from the field of VR, AR, and desktop VR are surveyed. The main section 4 presents our set of classification criteria, the menu taxonomy, and a discussion of resulting issues. Finally, section 5 concludes this paper.

2. Related work

The work presented here builds on a large body of previous work from different areas, such as virtual, augmented, and desktop virtual reality research. In addition, the taxonomy introduced in this paper relates to previously published classification approaches. Thereby we are mainly interested in techniques and 3D widgets [CSH*92] for application or system control.

In their fundamental work [JE92] Jacoby and Ellis provide a frame of reference for the design of virtual menus. They considered various design characteristics of menus, among them *invocation, location, reference frame, highlighting, selection*. They were taken into account in the development of our classification criteria (see subsection 4.1).

A comprehensive overview for the field of interaction techniques for immersive VEs is given in the book on 3D user interfaces by Bowman et al. [BKJJLP04], where techniques are classified in terms of task decomposition. The main categories identified are *selection, manipulation, travel, wayfinding, system control,* and *symbolic input*. They divide system control methods in *graphical menus, voice & gestural commands,* and *tools*. A further subdivision of graphical menus (being in the focus of this work) was conducted by means of *adapted 2D menu, 1-DOF menu, 3D widget,* and *TULIP*. This subdivision appears to be slightly arbitrary mixing DOF, origin and interaction devices as classification criteria. Especially the application developer is not assisted with this allocation of menus, since it is difficult to make an appropriate selection from it. We would like to continue this work by especially providing detailed criteria for building a taxonomy of menu solutions also including AR and desktop VR techniques. From the mentioned characteristics *placement, selection, representation,* and *structure* [BKJJLP04] we incorporated some in our classification categories presented in subsection 4.1.

Kim et al. investigated in their study [KKP*00] the usability of various menu presentation and multimodal selection schemes in immersive virtual environments. They reclassified several 2D and 3D menu presentation styles in VEs and identified five major menu display methods: *pull-down, pop-up, stack menu, object-specific, oblique/layered*. Then, by viewing the menu selection task as a composite task of *positioning* (manipulation) and *making a command*, and furthermore assigning different interaction modalities for each subtask, they identified 13 possible menu selection methods. The suitability of various combinations is compared and evaluated. Though it is one of the few papers entirely devoted to menu techniques it is yet limited to list menus in immersive environments and does not provide a comprehensive survey.

A comparison of specific VR menu systems was presented by Bowman and Wingrave in [BW01]. In this work the design of the TULIP menu is introduced and compared to the two common alternatives floating menus and pen and tablet menus in an empirical evaluation. Again, this work belongs to the few devoted solely to menu techniques.

All of the presented papers so far only address menus for immersive virtual environments. They do not consider desktop VR or AR solutions. Though various interaction techniques were also developed in the field of augmented reality in the past few years, to our knowledge there exists no classification work or taxonomy, especially not for menu techniques.

3D interaction in the field of desktop VR is usually done with the help of 3D widgets [CSH*92]. Dachselt and Hinz presented in [DH05] a widget classification scheme according to the criteria interaction purpose/intention of use, which influenced this work. It is the first classification also devoted to desktop VR. The following main categories were identified: *direct 3D object interaction, 3D scene manipulation, exploration & visualization,* and *system/application control*. As part of the latter our approach nicely fits into the menu selection subcategory. In [DH05] a simple taxonomy of menu widgets is also presented by means of *temporary option menus, single menus,* and *menu hierarchies* along with examples. This can be taken as a starting point for a more systematic and comprehensive approach including AR solutions, too.

3. Surveying existing 3D menu techniques

In order to classify existing menu techniques it is first of all necessary to find and analyze existing solutions to get an overview about state-of-the-art 3D menus. Our survey examines previous literature including the field of virtual reality, augmented reality, and desktop VR. According to the classification of Bowman et al. [BKJJLP04] we concentrate on graphical menus and do not further consider menus with voice or gestural commands. Since menus are often consisting of or employing 3D widgets, the focus of this work lies on classifying interactive 3D widgets, which meet the criteria of a geometric representation as postulated by Conner et al. [CSH*92]. In addition to that, techniques which do not require a very specific I/O setting (usually an input device) are naturally of more interest due to their generalization potential for various AR, VR, and desktop VR settings.

It can be observed that most of the menu solutions found in the literature were developed within the context of some broader system or application, thus being rather a by-product than a specific 3D menu contribution. Exceptions from that are recent developments such as the *command & control cube* [GC01], *TULIP menu* [BW01], *ToolFinger* [Wes03], *Spin Menu* [GB05], or *generalized 3D carousel view* [WPV05]. However, most of the literature stems from the middle of the nineties and is rooted in VR research.

The following three subsections roughly group the 3D menu solutions we have found with regard to their origin. Though we did our best in providing a comprehensive survey, some of the solutions developed in the past 15 years might not appear here. This is partly due to the fact that with similar solutions not all implementations are listed here. All surveyed menus can also be found online [Sur06] in a list including their properties.

3.1. Menus from immersive and semi-immersive VEs

As already pointed out earlier, the largest number of 3D menu techniques comes from this area. The embodiment of **2D solutions in 3D environments** started with the introduction of WIMP-elements into VE. Examples are the *pop-up and pull-down 3D virtual menus* by Jacoby and Ellis [JE92] or the work done by Angus and Sowizral [AS95] by means of generally integrating a 2D interaction metaphor into 3D virtual environments. By melting the 3D interaction metaphor of a hand held virtual tool with the software support available with a 2D user interface tool the user is provided with familiar interaction concepts. However, associated 2D interaction techniques, such as click-and-drag remained an element of desktop environments only [DD05]. Attempts were made by means of making 2D *X-Windows widgets* available within 3D contexts. In [CRF97] a hybrid 2D/3D user interface is described for immersive modeling, where *X-Windows menus* are cloned to provide each eye its own copy.

The 'classical' *floating menu* (see Fig. 1a) was implemented in various VR scenarios, where the user needs to make the 3D cursor intersect the appropriate menu choice. It changes the one-dimensional task (choosing from a list) into a three-dimensional and increases the possibility of making errors [Han97]. Typically, the user's finger or some sort of laser-pointer is used for selection in combination with a button-click on a physical device for activation. Selection from 2D pop-up menus is mostly done by casting a ray from the 3D mouse position. Directly touching menu items is often difficult, since menus might be out of reach [JE92]. Amongst others, implementations can be found in [BL91,Min95,WG95,PS96,CFH97,vTRvdM97]. To pick an example, two-dimensional menus are included in the ISAAC interaction techniques [Min95]. They are virtual equivalents of conventional workstation pull-down menus floating in three-dimensional space. Extensions of floating menus include scrolling a longer list of items, for example implemented as a virtual menu in [SPH*95].

A somewhat different menu solution was presented with the HoloSketch project [Dee95] for a fish-tank VR setting. The *3D fade-up menu* (see Fig. 1b) is a 3D pie menu which pops up by depressing the right wand button. Thereby the scene is faded out and the menu faded in at the same time. To select a menu item, the user pokes the wand tip at one of the circularly arranged buttons.

Glove-based menu selection allows a more natural style of selection by means of using the fingers and hands. Typically, finger pinches are used to control a menu system, for example in the glove-based *menu system Tinmith* [PT01] or a fingertip-based interaction technique called *FingARtips* [BVBC04]. Whereas these menus were developed in the context of AR (see below), the *TULIP menu* [BW01] (see Fig. 1c) was especially developed for VR settings. It uses Pinch Gloves, where up to 16 menu items are assigned to different fingers and a pinch between a finger and the thumb is interpreted as a menu selection.

Speech recognition enhanced menus. One of the problems resulting from the usage of instrumented gloves for gestural and spatial input is that hands can be too encumbered to use other tools [Han97]. That was the motivation for the development of the *hands-off interaction technique* for menu display which involves the presentation of menu items as a 2D overlay onto the 3D world. Textual menu items are displayed on a viewplane, which moves relative to the user. The menu items are selected via a speech recognition system [Dar94].

Hand-held menus are improving upon the previously mentioned solutions in that they allow a virtual menu (usually an object palette) being controlled with one hand, whereas the other is selecting items from it. Prominent examples are the interaction techniques developed in the CHIMP project by Mine [MFPBS97]. The *tear-off palette* contains miniature representations of available objects which the user can grab and add to the scene by moving his hand away from the palette. Another technique developed in this project is the *look-at-menu*, which can be attached to any object in the environment including the user. It is activated by the intersection of a user's current direction of view with a hot point representing the menu. To select a new item the user moves his head to look at the desired item.

Prop-based 'physical menus'. Some research was devoted to 3D widgets and especially menus being attached to physical surfaces. Generally these are tracked physical surfaces on which menus are placed. The menu items can be selected with a tracked physical pen/stylus why these menus are also called *pen-and-tablet menus* [BKJJLP04]. An example for this type of menus is the *3D Palette* by Billinghurst et al. [BBMP97] (see Fig. 1d). It is an interface for creating virtual scenes using a tracked tablet and digitizing pen. In addition to the two-dimensional tablet input menu items can

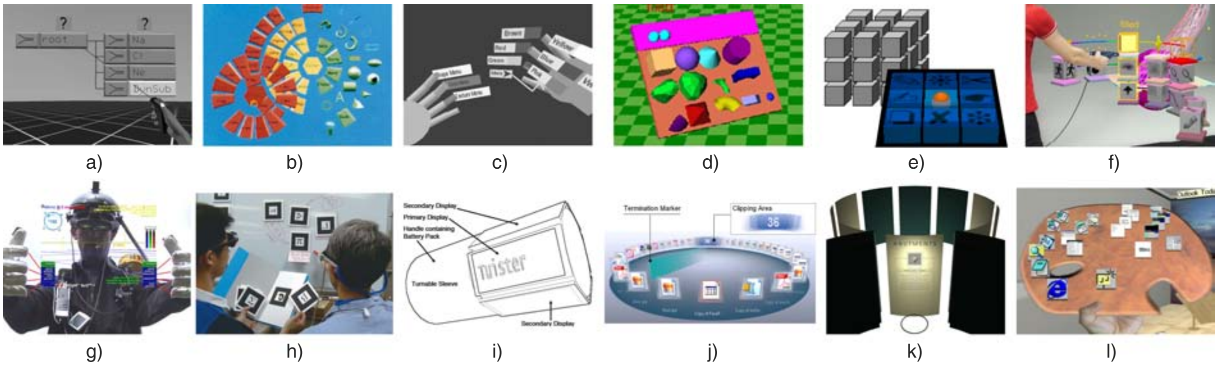

Figure 1: *VR-Menus (top): a) floating menu [vTRvdM97] b) fade-up menu [Dee95] c) TULIP menu [BW01] d) 3D Palette [BBMP97] e) C^3 [GC01] f) spin menu [GB05]. AR-Menus: g) Tinmith-Hand [PT01] h) menu tiles [PTB*02] i) TUISTER [BGK04]. Desktop VR menus: j) generalized 3D carousel [WPV05] k) revolving stage [Dac99] l) start palette [RvDR*00]*

also be selected by issuing vocal commands. Another similar approach is the *Virtual Tricorder* [WG95]. It confines 2D interaction and information to a virtual handheld object. A 2D tricorder-anchored menu lets users select among different tools. Since the menu is attached to the interface, the target acquisition is a relative task, thus allowing greater performance.

Workbench Menus. The responsive workbench and similar configurations are very attractive for direct manipulation [GC01]. Typically menus are used by means of a toolbox containing various 3D-icons. Interaction is done with the stylus or by pinching with the gloves as for example in [CFH97]. Another workbench system introduced the *virtual tool rack* [PS96]. It holds buttons with icons to enable tools and activate different modes of operation. Interaction is done with a two-handed approach, where 3D-intensive operations are performed with the 3D stylus while the 1D row of buttons can be controlled with a constrained mouse. The *command & control cube (C^3)* [GC01] (see Fig. 1e) developed for a holobench setting presents a 3D equivalent of the quick keyboard hotkey mechanism known from WIMP interfaces. This menu solution was inspired by marking menus and facilitates the quick selection of commands with a 6-DOF tracked button. Thereby menu items are arranged into a cubic configuration. Another quick menu selection technique based on marking menus was introduced with the *Spin Menu* [GB05] (see Fig. 1f). Items are arranged on a portion of a circle and controlled by rotating the wrist in the horizontal plane. Since at most 9-11 items can be displayed on a ring, hierarchical spin menus are suggested with crossed, concentric, or stacked layouts.

Menus being attached to the user's body take advantage of proprioception during body-relative interaction. The already mentioned *look-at-menus* employ head orientation instead of the traditional hand position to control the cursor. Thus an intuitive way to select an item is provided by simply looking at it [MFPBS97]. Other 1-DOF menus, such as the *ring menu* of the JDCAD system by Liang and Green [LG94] instead require the movements of hand and wrist to rotate the menu and select an object.

3.2. Menus from augmented reality applications

Basically, augmented reality applications use **similar menus to those in VR**. Some of the solutions even aim at combining both domains, for example the *Tinmith-Hand menu system* [PT01] (see Fig. 1g). It is a glove-based system, where each finger maps to a displayed menu option at the border of a display. The user selects one item by pressing the appropriate finger against the thumb. A vision based tracking system at the same time allows the user to manipulate 3D objects. The eight item menu is placed on the bottom of the user's display to navigate the options and select the actions required. This system resembles a menu style quite common before the introduction of the mouse, which is pressing a function key to either activate a menu item or display a submenu. With the *FingARtips* 3D object menu [BVBC04] gloves are also used. This time the gloves have three markers, which are used for hand tracking, e.g. for selecting objects or pressing buttons. By means of gesture recognition using the two fingers, objects can be selected and grabbed from the menu.

A tablet-and-pen based approach was developed in the Studierstube project with the *Personal Interaction Panel* as a two-handed interface for AR applications [SG97]. Controls associated with a magnetic tracked panel can be manipulated in a desktop manner using a pen. For menu selection a tool-palette (3D clipboard) is employed. Besides browsing objects from a palette, drag-and-drop operations to and from the surrounding scene are supported.

Typically, AR applications address the domain of collaborative planning by seamlessly combining real and virtual objects. In the *mixed reality stage* planning application [BGH*04] virtual models can be loaded from a *virtual menu*. Menus are opened by issuing a single modal voice command or alternatively by pressing buttons of a wearable input device. Navigation in the menu hierarchy and selection of entries is accomplished by using the view pointer (crosshair shown in a head mounted display) and issuing a voice command.

Whereas the previously mentioned approaches are similar to VR solutions, augmented reality especially features computer vision techniques (e.g. for tracking the user's hand on a virtually augmented table) and integration with the real world by **using physical objects for interaction** as in tangible and graspable user interfaces. Take for example the TILES interface [PTB*02] where a book serves as a catalog or menu in presenting different virtual instrument models on each page. So-called *menu tiles* (see Fig. 1h) make up a book with tiles attached to each page. As users flip through the pages, they can see virtual objects attached to each page, which can be chosen and copied from the book. Beside these marker-based interaction techniques using props like pads or paddles, other approaches use tools with real-world correspondence. An example is the *TUISTER* [BGK04] (see Fig. 1i), which is a tangible interface for presenting and navigating hierarchical structures. Menu items are shown on a real cylindrical display, e.g. consisting of small discrete panels arranged to form a cylinder. This display part can be rotated by the hand against the second part of the TUISTER interface, the handle held fixed by the other hand. By changing the rotation between both hands, menu hierarchies of arbitrary depth can be examined.

Another **explicit AR menu solution** avoiding complex hand-based or tool-based interfaces is a *3D spherical menu* as presented in [FC03]. The menu is based on spherical menu layers and can be operated by simple 2D input devices, thus being suitable for rapid prototyping and testing of mobile AR applications. It is basically a 3D counterpart to the classical 2D desktop menu, which can alternatively operated by direct manipulation, i.e. using a hand-based interface.

3.3. Menus from the field of desktop VR

This area mainly comprises **widget based solutions**, since 3D widgets allow the subdivision of higher-dimensional interaction tasks into sub tasks being suitable for lower-dimensional input devices. Many of the solutions from the field of virtual and augmented reality can also be used in 3D desktop applications. A huge advantage of desktop solutions is the familiarity and high precision possible with well-known interface devices. Interaction is usually done by the mouse or keyboard and therefore often requires additional 3D widgets. Take for example the *ring menu* in a desktop version [Wid05], where buttons are added to allow for rotating the ring to the left or right side. Another recent ring menu approach addresses the problem of a potentially high number of menu entries, such as for document browsing. It is the *generalized 3D carousel view* presented in [WPV05] (see Fig. 1j). Document icons are arranged on a ring. Through the use of a clipping area and a termination marker even large amounts of menu items can be displayed. The menu is operated by click-selection, stepwise and free rotation using mouse or arrow keys. The *revolving stage menus* (e.g. in [Dac99] (see Fig. 1k), also called *rondel* in [PRS97]) improve on that in displaying a number of conventional flat menus arranged in a circular manner. The stage can be rotated until the desired single menu faces the user. Afterwards a selection can be made from this menu.

Since screen space is limited even with modern displays, 3D solutions providing a **detail-and-context visualization** were developed. Whereas the well-known *cone trees* [RMC91] and derivate solutions focus on the visualization of hierarchical information, other solutions focus on the fast interaction and can be rather seen as menu solutions. Take for example the *collapsible cylindrical trees* technique [DE01] which uses rotating cylinders to display menu items of one menu. Submenus are made possible by smaller cylinders appearing from the super menu cylinder, which is very much like a telescope. Other higher level menus are squeezed but still visible, thus providing focus and context at the same time. Another work related to menu hierarchies is the *polyarchy visualization technique* described by Robertson et al. [RCCR02]. Separate hierarchies including the same item (e.g. a person) can be linked in 3D space and navigated using animated techniques.

It is also worth looking at some commercial or experimental **3D desktop solutions** in order to find interesting spatial menu solutions. We have investigated Win3D [W3D05], 3DNA [3DN04], and Sun's project Looking Glass [Sun05]. Several 3D menu widgets can be found, among them a *hinged menu* [W3D05] containing 3D objects on different fold-away layers representing system controls for peripheral devices. Most menus are various geometric arrangements or layouts of items, e.g. in *horizontal or vertical stacks, drawers, panoramic walls* [3DN04], *shelves*, or even *wardrobes*. The 'it3D' interactive toolkit library for developing 3D applications introduced in [OAS02] provides several 3D widgets including *combo boxes* and *list menus* being very close to traditional 2D interface elements. A rather unusual approach with a loose layout was chosen with the *start palette* of the Task Gallery [RvDR*00] (see Fig. 1l), presenting program and document icons on a 3D painter's palette.

4. A Taxonomy of three-dimensional menus

As we have seen in the previous survey section, there exist a huge number of 3D menu techniques. The way the solutions were ordered, i.e. by their *origin*, already constitutes a first categorization. However, in order to better understand, describe, compare, and classify them we need to identify distinct properties. While analyzing specific menu solutions and related taxonomies in the field we came up with the following classification criteria and associated properties.

4.1. Classification criteria and menu properties

The following paragraphs list and describe the main criteria (i.e. axes of the taxonomy) and associated properties of 3D menu solutions. Examples were added from our survey to better illustrate the characteristics.

Intention of use. This category describes menus by means of answering the question: What does the application developer want the user to choose from and for which purpose? The *number of displayed items* is an important characteristic of a virtual menu. Certain menus only allow for a very limited number of options (e.g. 8 items in the Tinmith-Hand menu system [PT01] or 26 menu items for the $3 \times 3 \times 3$ cubic grid (minus the center) of the C^3 technique [GC01]). Others can contain virtually any number of entries (e.g. 2D scrollable lists in space). A limited number of items (e.g. on the top level) can be a serious constraint for designing and balancing an efficiently structured menu [Shn98].

This leads to the property of the menu's *hierarchical nature*. This is an important property reflecting the intention of use. We distinguish between the following four types:

- *Temporary option menus*. Allow the user to quickly select from a limited number (usually ≤ 7) of temporarily displayed items (mainly options). The menu is only invoked for a short time and vanishes after the selection. Typical representatives are the ToolFinger [Wes03] or the rotary tool chooser [Min95].
- *Single menus.* Basically the same like the first type, but displayed for a longer time or even visible all the time. The number of selectable items can be greater than with the first menu type, also arbitrary items can be displayed. This type includes toolbars and tool palettes such as [PS96, CFH97, BBMP97].
- *Menu systems.* This is the same like the second type but extended to contain a submenu for each entry (if appropriate). That is, menu systems are menu hierarchies with a depth of 2. This is exemplified with the revolving stage/rondel [Dac99, PRS97].
- *Menu hierarchies.* These menus allow an arbitrary number of items, which are arranged in an arbitrary number of sub menus (depth of hierarchy ≥ 3). This type resembles menu solutions well known from traditional desktop environments and is also called cascading menus or tree-structured menu [Shn98]. Examples for it are the TUISTER [BGK04] or the fade-up menus [Dee95].

Please note that the term menu system is used in traditional desktop environments for menu hierarchies with an arbitrary depth, whereas in this survey we make a distinction between menu systems and menu hierarchies for three-dimensional menus. We consider this to be reasonable, since there are many examples within the literature, where menu solutions exactly allow for displaying two hierarchy levels.

Appearance and Structure. The *geometric structure* describes the appearance of a menu in terms of the supporting geometry. This might be a rather flat list (as in floating 3D menus), a disc (e.g. ring menu [LG94] or carousel view [WPV05]), a sphere (e.g. Boule menu ball [Bou99]), a cylinder (e.g. TUISTER [BGK04]), cube (e.g. C^3 [GC01]), other platonic bodies or none at all.

Moreover, the *structural layout* describes how the items are arranged either on the supporting geometry or within space. This includes the types acyclic list, cyclic list (usually ring), matrix, free arrangements (e.g. in the start palette [RvDR*00]) and layouts following the geometric structure. Geometric structure and layout have a significant influence on memorability and interaction speed.

The *type of displayed data* is an important property, too. We differentiate menu options appearing as:

- *3D-objects*, i.e. previews (e.g. on a 3D palette [BBMP97] and many more)
- *Text entries* (e.g. with hands-off interaction [Dar94] or TUISTER [BGK04])
- *Images*, i.e. icons (e.g. C^3 [GC01])
- *Images and text combined* (e.g. generalized 3D carousel view [WPV05])
- *3D-objects and text combined* (e.g. 3D fade-up menu [Dee95])

Note that it essentially influences the selection of an appropriate menu, whether a geometric object (e.g. a product) or another abstract option (e.g. screen resolution) shall be chosen. In addition to that the well-known and still remaining problem of text readability in virtual environments also prohibits certain menu structures.

In addition to that, the *size and spacing of menu items* plays an important role for selection and overall space consumption. Usually flat menus or simple text lines need fewest space, whereas platonic bodies or revolving stages consume far more space.

Placement. This category was introduced by [BKJJLP04] and comprises similar categories presented in [KKP*00]. According to it menus can be placed in the following ways:

- *world-referenced* (most desktop VR menus)
- *object-referenced* (e.g. combo box in [OAS02])
- *head-referenced* (e.g. look-at-menu [MFPBS97])
- *body-referenced* (e.g. TULIP [BMLP01])
- *device-referenced* (e.g. tool menu of the responsive workbench [CFH97], PIP tool-palette [SG97], or fade-up menu [Dee95])

In addition to the general placement, *orientation* also plays an important role and influences the space needed. An example of a menu always facing the user is the hands-off interaction menu technique [Dar94], another for the fixed location at the bottom of a display the Tinmith-Hand menu system [PT01]. Within this context also the question arises, whether menus can be *repositioned* by the user, either to avoid occlusion or for personal preferences.

Invocation and availability. This category comprises menu properties, which describe how users actually invoke a menu (make it appear or activate it). The first characteristic is the *visibility*. Menus can be visible all the time (such as in typical 2D applications), can be temporarily displayed for the duration of the selection or can be shown as long as the user wants it to appear. *Invocation* of non-visible menus can result from

- *Selecting an icon* or other miniature
- *Context dependent activation* related to either an object, other menu (for submenus) or some specific background
- *Free activation* at an arbitrary point (menu hidden)
- *No action*, menu persistently visible

Activation can be generally done by pressing some virtual or physical button, pinching two fingers or doing a gesture. To provide an example, in the look-at-menu [MFPBS97] the user's current direction of view activates a pop-up menu from a so-called hot point (e.g. a small red sphere). Virtual menus can also be hidden in locations fixed relative to the user's body, e.g. above the current field of view. An advantage is that menus attached to the user's body can be moved with the user as he moves through the environment, thus being always within reach [MFPBS97].

Animation is also an important property of virtual menus. Although it can be associated with the category appearance, it is listed here, since it very much affects the user's interaction with the menu. Take for example some of the polyarchy visualization techniques described by Robertson et al. [RCCR02]. Without animation techniques it would hardly be possible to explore the multiple intersecting hierarchies. It is interesting to note that there are far more animation possibilities in 3D space than in 2D. Some of them are: blending, zooming-in, opening, expanding, collapsing, turning, rotating, fanning or drawing out menus or parts of it.

The property *collapsibility* relates to the previously mentioned, because it allows for compressing or temporarily hiding a menu without completely removing it. Usually animation techniques are employed to expand or collapse parts of the menu, for example with the collapsible cylindrical trees menu [DE01]). Thus the user is still provided a coherent interaction with a menu without losing context or position.

Interaction and I/O setting. First of all the proposed *interaction device* is of great importance. The menu solutions described in the literature include almost all devices and input channels, such as mouse, spaceball, gesture and speech, 6-DOF tracking devices, computer vision, pen and tablet menus, pinch gloves, and other two-handed solutions. According to Darken and Durost [DD05] *dimensionality* plays a crucial role in interaction design, especially the proper match of the dimensions of interaction techniques and interaction tasks. With floating menus used in VR scenarios the user needs to make a 3D cursor intersect the appropriate menu choice. The one-dimensional task (choosing from a list) is transformed into a three-dimensional one and increases the possibility of making errors [Han97]. It was demonstrated in [DD05] that dimensional congruence results in superior performance.

Another characteristic associated with interaction is appropriate *feedback/highlighting* provided by a menu [Shn98]. There are many different solutions to this problem, including movement of items or their animation, highlights, item changes in color, brightness, geometry, size as well as additional selection geometries. A related issue is the appropriate *visualization of the selection path*. Whereas in 2D menu systems this is a matter of course and state of the art, 3D menu systems and hierarchies rarely support it. An exception is the spin menu [GB05], which displays the path as stacked objects (compare Fig. 1f).

In addition to that, many of the described solutions exhibit input *device dependence*, since they were developed in specific VR or AR settings. This is exemplified with the tool finger [Wes03] or the TUISTER [BGK04] requiring special hardware settings. Output devices also influence interaction with menus. Take for example 2D menus in a virtual environment displayed on a stereoscopic display, where problems such as appropriate display depth, disparity, or occlusion arise [Han97]. Other displays, e.g. head mounted displays exclude the user from using devices such as mice or keyboards. Summarizing these dependencies many 3D menu techniques support a certain *application type and I/O setting*. This could be a specific virtual reality or augmented reality setting as well as a desktop VR application type described in the original paper. Some of the menu solutions can and should be generalized to other application types and system settings, even to mobile devices.

Combinability. This is a feature of a 3D menu describing whether it can be combined with other menu solutions to build menu systems or hierarchies. Some single menus are well-suited to be combined to build a menu system; others prevent combination due to their geometric structure. Menus sometimes use a different technique especially for the top level. Take for example the revolving stage/rondel [Dac99, PRS97], where a ring menu is used with simple floating menus at each position. Another example is the spin menu [GB05] combining different approaches for displaying submenus (e.g. ring and stack menu). Again, animation techniques are employed in combined solutions to establish the link between them.

With the criteria and properties described in this subsection (see table 1 for a summary) we define the design scope for three-dimensional menus. Although certainly neither all orthogonal, nor equally applicable to every menu solution

Intention of use	
Number of displayed items	limited or not
Hierarchical nature	temporary option menu, single menu, menu system, menu hierarchy
Appearance and Structure	
Geometric structure	None, list, disc, sphere, cylinder, cube…
Structural layout	acyclic list, cyclic list (ring), matrix, free arrangement, geometric structure
Type of displayed data	3D-objects, text entries, images, images & text, 3D-objects & text
Size & spacing of items	
Placement	
Reference	world, object, head, body, device
Orientation	
Repositioning	
Invocation and availability	
Visibility	whole time, temporarily, user-dependent
Invocation	icon/miniature, context dependent, free, none
Animation	various ways
Collapsibility	
Interaction and I/O setting	
Dimensionality	interaction device and task
Feedback/highlighting	various ways
Visualiz. of selection path	
Device dependence	input/output devices
Application type	VR, AR, Desktop VR, 3D-Mobile
Combinability	

Table 1: *Summary of 3D menu classification criteria*

they form a reasonable basis for characterizing or evaluating existing approaches. Most of the surveyed menu solutions were described according to these criteria. Due to space limitations of this paper it can be found as a comprehensive table online [Sur06].

4.2. A taxonomy according to the intention of use

The survey of three-dimensional menu solutions presented in section 3 already constitutes a first rough classification according to the criterion *application type* (or *origin*). In addition to that, the classification criteria presented in detail in the previous subsection may serve as axes of taxonomies such as the one presented here as well as other classifications. In our opinion purely theoretical or academic classifications would be less of real help for the 3D user interface developer. That is why we chose the main characteristic *intention of use* as one being well suited for building a taxonomy. Having a mixed reality application developer in mind who searches for an appropriate 3D menu solution, this criterion allows to make the fundamental decision on using a *temporary option menu, single menu, menu system*, or *hierarchy*, which is necessary for most applications.

It seems to be sensible to further divide the taxonomy. The category *appearance and structure* lends itself as a secondary axis for further subgrouping existing solutions. Typically, virtual environments also possess a basic spatial structure and appearance, which should be matched by an appropriate choice of menus. Application developers often decide on the structure (and also position) of a virtual menu after having made the basic decision e.g. on using a full menu hierarchy. By combining the criteria *intention of use* and *structural layout* we conceived a taxonomy as depicted in table 2. We have applied this taxonomy to the examined menu solutions. Note that similar solutions were already summarized. In addition to that, an exclusive assignment is neither always possible nor necessary and some overlaps do exist.

Temporary Option Menus		
List		
	Pop-up & pull-down menus [JE92, WG95]	
	Look-at menus [MFPBS97, BGH*04]	
Ring		
	Rotary tool chooser [Min95]	
	Spin menu [GB05]	(Fig. 1f)
Matrix		
	Command & Control Cube [GC01]	(Fig. 1e)
Geometric structure		
	Boule menu ball [Bou99], Tool finger [Wes03]	
Single Menus		
List		
	Drop-down menus [SPH*95,Min95,CRF97, AS02]	
	FingARtips [BVBC04], Tinmith-Hand [PT01]	
	Pen-and-tablet menus [AS95]	
	Chooser [Wid05], virtual tool rack [PS96]	
Ring		
	Ring menus [LG94, Wid05]	
	Generalized 3D carousel view [WPV05]	(Fig. 1j)
Matrix		
	3D palettes [MFPBS97,CFH97,SG97,BBMP97]	(Fig. 1d)
	Panoramic wall [3DN04]	
Geometric structure		
	Shelves, horiz./vertical stacks [KKP*00, W3D05]	
Free layout		
	Menu tiles book [PTB*02]	(Fig. 1h)
	Start palette [RvDR*00]	(Fig. 1l)
Menu Systems		
List		
	Spin menu with crossed layout [GB05]	
Ring		
	Revolving stage/rondel [Dac99, PRS97]	(Fig. 1k)
	Spherical menu [FC03]	
Geometric structure		
	Hinged menu, Cross chooser [W3D05]	
Menu Hierarchies		
List		
	Hands-off interaction [Dar94]	
	Tinmith-Hand with submenus [PT01]	(Fig. 1g)
Ring		
	3D fade-up (pie) menu [Dee95]	(Fig. 1b)
	Spin menu with concentric layout [GB05]	(Fig. 1f)
	Collapsible cylindrical trees [DE01]	
Geometric structure		
	Cone trees [RMC91], TUISTER [BGK04]	(Fig. 1i)
Free layout		
	TULIP [BW01]	(Fig. 1c)
	Polyarchies [RCCR02]	

Table 2: *Taxonomy of 3D widgets according to the criteria* intention of use *and* structural arrangement

4.3. Discussion

Looking at table 2 one can observe that the majority of solutions were developed for single menus including tool palettes. It does not come as a surprise, since not all VE applications need to have fully-fledged menu hierarchies. Since the border between temporary option menus and single menus can not be drawn sharply, solutions can be allocated to either of them. We do not consider this to be a disadvantage. The quick operation and limited number of items are practical reasons justifying a separation. Similarly menu systems can be seen as subclasses of menu hierarchies. As stated already in subsection 4.1, the distinction is useful, if one thinks of common cases, where an optimized menu system with hierarchy depth of 2 is sufficient.

We are aware of the limitations of this taxonomy, since there are always numerous ways of classifying techniques. However, due to the extensive list of categories presented in subsection 4.1, a number of other classification approaches can be imagined. In fact we have also investigated other classifications, e.g. by using and combining important criteria such as *intention of use*, *application type* (origin), *type of displayed data*, *placement*, or *dimensionality* of the interaction task.

However, not all mentioned categories and properties are suitable for a taxonomy of three-dimensional menus; some of them are better suited to just filter existing menu solutions in order to find an appropriate one. Queries of system developers could be answered such as 'I am looking for a menu hierarchy being operated with gloves in the field of AR' or 'Which solutions are available with a circular layout containing 4-20 items displayed as either 3D objects or icons'. To allow such queries, we developed an initial Web site [Sur06], where all surveyed solutions can be queried and ordered according to their properties.

This leads to some interesting **research directions:**
Community effort would be necessary to improve this site, since it is neither possible to overlook every single development in this field nor to describe every detail of a menu solution. This work needs to be continued. A Wiki-powered site could be of much help to the community and extend far from 3D menus to 3D interaction elements in general. Moreover, besides classifying techniques it is desirable to consistently specify them in order to achieve portability across various applications within the mixed reality continuum. Again, community involvement is needed, which might lead to future standardization in the field of 3D user interfaces.

To return to 3D menus as a subclass of interaction elements, several future developments are conceivable. We have seen (as with 2D desktop solutions) that acyclic lists dominate the field, whereas other geometric structures were rarely used by now (compare table 2). We consider them as possessing some potential for further developments, encouraged for example by the development of the command & control cube [GC01] or TUISTER solutions [BGK04].

Another area largely unexplored by now is the combination of several menu techniques. Recent developments such as the layout variants presented with the spin menu [GB05] show the potential. In addition to that, animation techniques could be applied more intensively, since they allow a smooth combination of various techniques and reduce the cognitive burden.

Since the taxonomy spans the design space for 3D menu solutions, it also aids researchers in identifying opportunities to improve or create novel virtual menu techniques. New techniques can be developed through a) combining existing menus, b) improving them c) developing new ones using empty or promising gaps within the taxonomy. To provide an example, we noticed that non-linear detail-and-context techniques were only rarely applied for 3D user interface by now, though they have a huge potential for accommodating a larger number of items or bigger hierarchies.

5. Conclusion

In this paper we surveyed a multitude of three-dimensional menu solutions from the area of virtual reality, augmented reality, and desktop VR. In order to describe, compare, and classify 3D menus, several characterizing categories and properties were presented along with a taxonomy considering the intension of use. The identified criteria do not only serve as axes of the presented taxonomy, but lay a solid foundation for further classifications. The taxonomy can be applied to evaluate the suitability of an existing menu solution for a particular mixed reality application. Thus it facilitates VE application developers the choice of appropriate widgets and techniques from the provided repertory according to selected criteria. Moreover, the design space described in this work allows researchers to create new menu solutions or to improve existing ones. We hope to have made a contribution to the field of 3D user interfaces in fundamentally examining this rather unexplored area of application controls in virtual environments. With it the ground is laid for an agreement on well-established 3D menu techniques eventually leading to standardization.

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