Chapter 12
On, Above, and Beyond: Taking Tabletops to the Third Dimension

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Abstract Extending the tabletop to the third dimension has the potential to improve the quality of applications involving 3D data and tasks. Recognizing this, a number of researchers have proposed a myriad of display and input metaphors. However a standardized and cohesive approach has yet to evolve. Furthermore, the majority of these applications and the related research results are scattered across various research areas and communities, and lack a common framework. In this chapter, we survey previous 3D tabletops systems, and classify this work within a newly defined taxonomy. We then discuss the design guidelines which should be applied to the various areas of the taxonomy. Our contribution is the synthesis of numerous research results into a cohesive framework, and the discussion of interaction issues and design guidelines which apply. Furthermore, our work provides a clear understanding of what approaches have been taken, and exposes new routes for potential research, within the realm of interactive 3D tabletops.

Introduction

Horizontal, direct touch tabletops, which overlay large display and input surfaces, have recently been the focus of numerous studies. As the display and interaction surface of the typical tabletop display is 2D, the majority of this increasingly large body of work has focused on 2D applications and 2D interactions. However, the tasks which we carry out on physical tables are commonly three-dimensional in nature. It is thus desirable to consider how such tasks could be carried out and supported by interactive tabletop systems.

Example applications are numerous: A team of doctors could plan a surgery with a 3D virtual representation of a patient's body; an architect could inspect a virtual

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3D model of a new building and its surrounding area before creating a physical model; a new car model could be displayed and annotated in a design studio before a 1-to-1 scale physical clay model is built. Given the inherent 3D nature of such applications, it would seem appropriate that designers consider 3D display, input, and interaction technologies.

A number of projects have extended the tabletop to the third dimension, using a wide variety of techniques and technologies. However, the majority of these applications and the related research results are scattered across various research areas and communities, such as interactive 3D graphics, virtual reality, augmented reality, and tangible user interfaces. An interface designer creating a 3D tabletop application is thus left with the challenging endeavour of sorting through the previous work to help make appropriate design decisions. In an effort to alleviate this problem, it is our goal to review and classify the previous work in interaction with 3D tabletops, in an attempt to provide insights for future applications and research.

In this chapter, we provide an extensive review of the previous work done with interactive 3D tabletops and present a taxonomy which unifies this research into a single cohesive framework. We then discuss interesting areas of the taxonomy which have yet to be explored, along with a set of general interaction issues and design guidelines which are applicable within this framework.

Interactive 3D Tabletops

While interactive tabletop research tends to focus on 2D applications and interactions, significant research has also examined 3D tabletop systems. Often such systems diverge from the typical tabletop setting, and thus may not be referred to as tabletop systems.

For the purpose of our work, we consider an interactive 3D tabletop system as any system which presents a 3D virtual environment on or above a horizontal surface. Furthermore, we do not limit our considerations to any specific interaction metaphors. While the majority of tabletop systems provide direct-touch interaction, systems using indirect touch and supplementary input devices have also been explored, so we consider similar systems for 3D tabletops.

It is our goal to review and categorize such systems to provide future researchers with a clear understanding of what has been done and what can be done in the realm of interactive 3D tabletops. In the following section we review the 3D tabletop platforms and applications which have been developed. Following this literature review we will categorize the previous systems into a taxonomy of interactive 3D tabletops.

Existing Technologies

In this section we review the existing technologies used to implement 3D tabletop systems.

Two-Dimensional Tabletop Technologies

The most basic implementation of a 3D tabletop system uses a 2D tabletop display. Such systems typically display two-dimensional imagery atop a multi-touch input device (Fig. 12.1). Although the underpinnings of such surfaces stem from the early 1980s [1], there has been a recent slew of technologies employed for multi-touch input on a tabletop [2–7]. While most commonly such systems are used for 2D applications, they can be used for interacting with 3D data. Roomplanner allows users to interact with floor plans, using an orthographic top-view projection [8]. The Active Desk is a large scale drafting table which designers can work in a similar method to a traditional drafting table [9]. More recently, there has been a surge of 3D interaction techniques being developed for 2D tabletop environments. Hancock et al. explored "shallow depth" interactions for 3D using a 2D tabletop [10]. Reisman et al. extended this work by developing a constraint based solution to provide direct 3D manipulation techniques [11]. Wilson et al. implemented a full 3D physics engine within a 2D table top environment to provide physically realistic 3D interactions [12], and later ex-tended this to allow users to pick objects up using a combination of 2D and 3D gestures [13].

Fig. 12.1 The microsoft surface table. A multi-touch input device with a two-dimensional display

Stereoscopic Technologies

With the use of stereoscopic technologies, the imagery presented by a 2D tabletop displays can be perceived as "popping out" of the table, potentially providing the user with a more realistic 3D experience. For example, the ImmersaDesk [14] is a large scale drafting table which provides stereoscopic images (Fig. 12.2). Users wear shutter glasses, and their viewing location is tracked so that the imagery is

Fig. 12.2 The ImmersaDesk [14] utilized a stereoscopic display, enabled with shutter glasses (ImmersaDesk^{TM} photo courtesy of the Electronic Visualization Laboratory at the University of Illinois at Chicago. ImmersaDesk is a trademark of the University of Illinois' Board of Trustees)

coupled with the user's viewpoint, providing a depth cue known as motion parallax. The user interacts with the imagery using a wand tracked in 3D. A similar platform is the responsive workbench, a virtual working environment that pro-vides virtual objects and control tools on a physical "workbench" [15, 16]. Users collaborate around the workbench, with shutter glasses and head tracking providing a non-immersive virtual environment. The virtual workbench is a smaller implementation, which also presents 3D imagery using shutter glasses [17]. However with the virtual workbench, the display is actually above the perceived location of the tabletop and facing down. The user looks through and interacts behind a half-mirror.

Augmented and Virtual Reality

In virtual reality systems, head mounted displays are commonly used to immerse the user in a 3D environment [18]. While head mounted virtual reality environments tend to be large areas which the user can explore, some systems use head mounted displays for table centric spaces, such as in surgical procedures [19]. A less immersive alternative, which allows the user to maintain the context of their surrounding environment, is to use a head mounted augmented reality display [20]. Such displays have been used for tabletop interactions, such as in VITA, a system supporting offsite visualization of an archaeological dig [21], which displays 3D imagery above a direct-touch tabletop. Another method of augmenting a physical workspace is to place a transparent projection screen between the viewer and the table, as in ASTOR, where virtual labels appeared alongside physical objects [22].

Tabletop Spatially Augmented Reality

The augmented reality systems described in the previous subsection augment the physical world by placing virtual imagery on a viewing plane. In this section we describe systems which augment the physical world by projecting imagery directly on to physical objects (Fig. 12.3). Such systems have been termed “Tabletop spatially augmented reality” [23]. An advantage of such systems is that supplementary hardware devices, such as glasses and head mounted displays, are not required. A disadvantage is that the display space is constrained to the surface of objects.

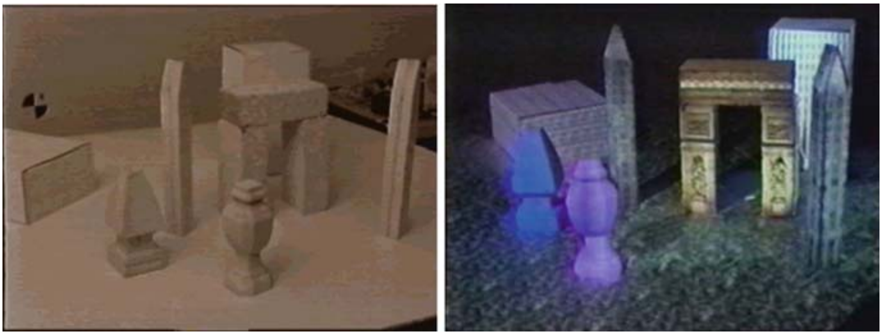

Fig. 12.3 Raskar et al.’s spatially augmented reality

Illuminating Clay [24] and Sandscape [25] are two examples of tabletop spatially augmented reality systems. In these systems, users interact with physical clay and sand, with the deformations being sensed in real time, and virtual imagery being projected on to the surface. In URP [26], physical architectural placed on a workbench are augmented with dynamic virtual imagery projected on to the scene. With tablescape plus [27], animated objects are projected on to small, vertical planes which can be moved around the table. Raskar introduced Shader Lamps, where dynamic imagery is projected onto physical objects, in a way that gives the illusion that the objects are moving, or the display conditions, such as lighting, are changing [28]. While initially non-interactive, follow-up work demonstrated dynamic shader lamps, which allowed users to virtually paint the physical objects [29].

Three-Dimensional Volumetric Displays

Volumetric displays present imagery in true 3D space, by illuminating “voxels” (volumetric pixels) in midair (Fig. 12.4). Favalora provides a thorough survey of

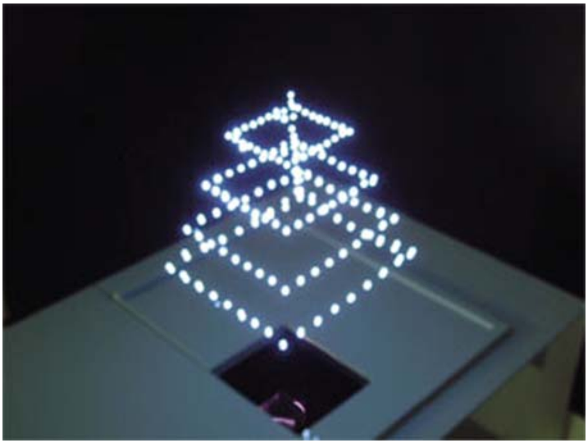

Fig. 12.4 A volumetric display lights a point in actual 3D space

the various technological implementations of volumetric displays [30]. The true 3D imagery in volumetric displays has been shown to improve depth perception [31] and shape recognition [32].

Besides providing true 3D images, the main difference from the other 3D tabletops displays is that volumetric display are generally enclosed by a surface. This means that users cannot directly interact with the 3D imagery. Balakrishnan et al. explored the implications of this unique difference to interaction design by using physical mockups [33]. More recent working implementations have allowed users to interact with the display by using hand and finger gestures on and above the display surface [34], and by using a hand-held six degree-of-freedom input device [35]. Although not truly three-dimensional, a similar spherical display was demonstrated by Benko et al. [36]. With this display, interactions and display were con-strained to the planar surface of the sphere.

Taxonomy

We have provided an overview of the existing 3D tabletop display technologies. As discussed, a number of implementations have been explored, each with their own benefits and drawbacks. However many of these research results are scattered across various research areas, without any overall organization. Complicating the matter is that while all of the work fits our description of a 3D tabletop research, many of the results were not intended to be considered tabletop research. In some cases the interactive tabletop research area had yet to be recognized. Such work may be overlooked when tabletop researchers start considering approaches for 3D applications.

With the outlined previous work in mind, we now define a taxonomy of the various implementations of interactive 3D tabletops. Our hope is to help future re-searchers understand the possible design space of interactive 3D tabletops, clarify which aspects of the design space have been explored, and expose possible implementations which have yet to be considered. This taxonomy will also serve as a basis for a discussion of specific interaction issues and design guidelines applicable to the various areas of the taxonomy, which we will provide in section "Interaction Issues and Design Guidelines". Our taxonomy is organized into 3 main areas: display properties, input properties, and physical properties (Fig. 12.5).

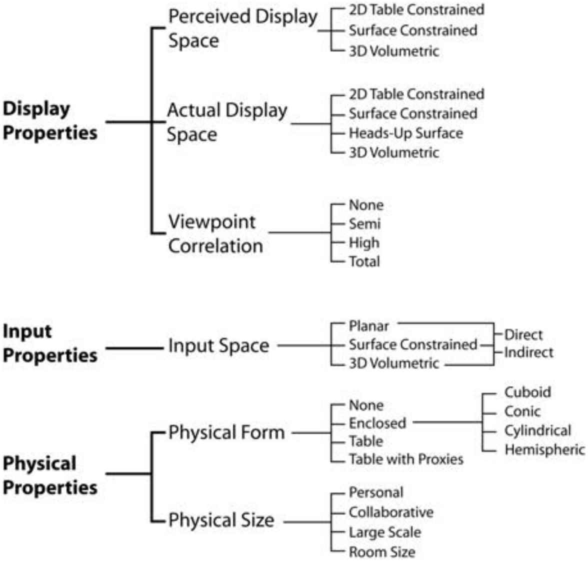

Fig. 12.5 Taxonomy of interactive 3D tabletops

Display Properties

The first main area of the taxonomy is the display properties. We consider the perceived and actual display spaces, along with the correlation between the user's viewpoint and the provided viewpoint of the imagery.

Perceived Display Space

The perceived display space is defined as the spatial location for which displayed imagery is perceived to be based on stereoscopic depth cues.

2D Table Constrained: In a traditional 2D tabletop display, the display space is 2D. Even when 3D imagery is displayed using a perspective projection on the table [10, 13, 12], we still consider the display space to be 2D if no stereoscopic depth cues are provided.

Surface Constrained: In tabletop spatially augmented displays, imagery is projected onto the table surface and physical proxies. An interesting variation is Second light [37], where imagery can be projected through the table by an under-mounted projector, onto objects above the surface. We term the resulting display space as surface constrained. While the displayed imagery exists in 3D space, the imagery itself is 2D.

3D Volumetric: When stereo cues are provided, via a head mounted display, shutter glasses, or a volumetric display, the perceived display space is truly 3D (Fig. 12.6).

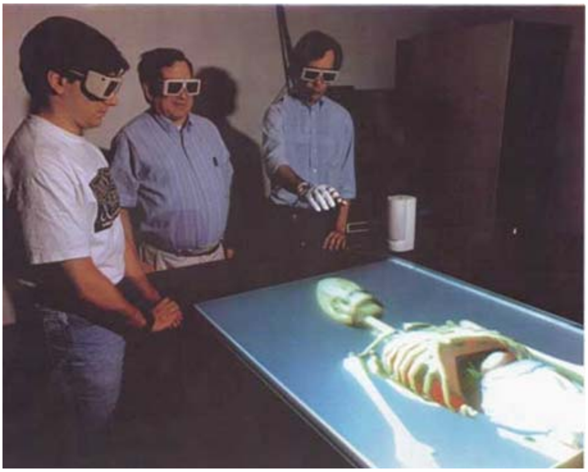

Fig. 12.6 The responsive workbench's display was constrained to the table, with false 3D created through shutter glasses

Actual Display Space

The actual display space considers where the actual displayed imagery exists. While this property is not meant to impact the user's perception of the imagery, it has been shown to affect the user's depth perception [31] and performance in three-dimensional tasks [38]. It is also an important property to consider as it will affect overall experiences and interaction affordances [18].

2D Table Constrained: In a tradition tabletop setup, the actual display space is also the 2D table itself. In systems where users wear stereo shutter glasses, the actual display space is also constrained to the table, even through the user perceives 3D imagery.

Surface Constrained: In the spatially augmented reality applications, which project imagery onto physical proxies, the actual display space is constrained to surfaces on and above the table (Fig. 12.7). Although the actual display space exists in 3D, we do not consider it to be truly 3D or volumetric, since imagery cannot exist anywhere in the working volume.

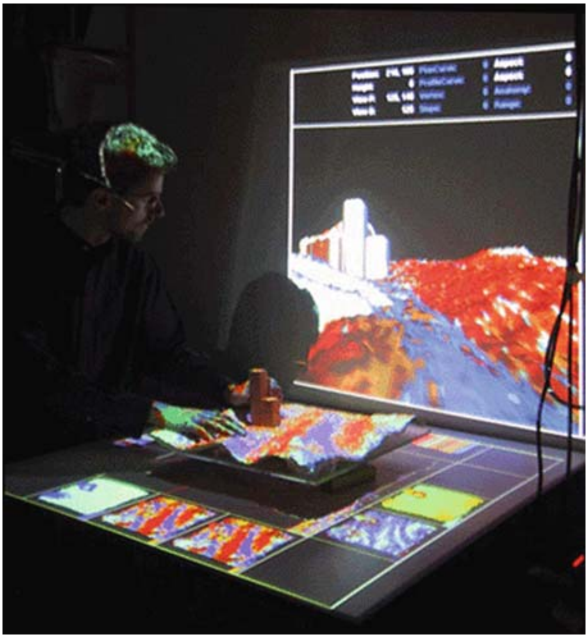

Fig. 12.7 Illuminating clay projected onto curved surfaces

Fig. 12.8 Benko et al.'s hybrid virtual environments used a head-mounted display to insert imagery into the space between the user and the table

Heads-Up Surface: When the actual display space is on a transparent surface between the user and table, we term the display space as Heads-up-Surface. This is the case when using a head mounted display, or when virtual imagery is projected on a see-through display plane (Fig. 12.8).

3D Volumetric: When imagery can appear anywhere on or above the display, the display space is 3D volumetric. Currently, volumetric displays are the only technology with this capability.

Viewpoint Correlation

When we move our heads in the physical world our viewpoints change, which affects the visual images which we receive. The last property of the display which we consider is the range of viewpoints which can be obtained of the imagery by physically moving around the display. For this property, there are no discrete values; we categorize the technologies based on 4 magnitudes.

None: In a traditional tabletop set up, the user's viewpoint is independent of the displayed imagery. The displayed image is static, regardless of the users viewing location.

Semi: In some systems, such as spatially multiplexed autostereoscopic displays [39], a finite number of viewpoints are provided (Fig. 12.9). With such systems, the transitions from one viewpoint to the next can be choppy, but the basic motion parallax effect is provided.

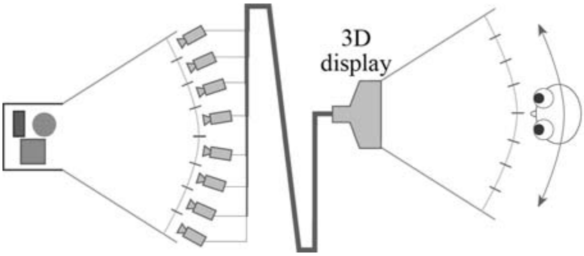

Fig. 12.9 Dodgson described autostereoscopic 3D displays, in which multiple views are available to the user depending on their head position. The set of viewpoints is limited to horizontal position and an assumed vertical position, providing only semi-correlation to the user's viewpoint

High: High viewpoint correlation means that the viewpoint of the virtual imagery continuously changes with the user's viewing location, with limited exceptions. This can be achieved with a standard 2D display and tracking the user's head (Fig. 12.10), or by using a volumetric display. The expectation with such technologies is when the user moves below the horizontal plane of the table. In this case, the user will see the bottom of the table, not the bottom of the imagery on top of the table. This is also the case when working with a physical table.

Total: When using a head mounted display to create a virtual reality tabletop experience, total correlation between the user's viewpoint and the displayed imagery can be achieved. Without the presence of a physical table, users could potentially view imagery from below the horizontal plane of the virtual table.

Input Properties

An important consideration for 3D tabletop displays is how the user interacts with the displayed imagery. A full categorization of input technologies and techniques

Fig. 12.10 The 2-user responsive workbench provided highly correlated views by displaying 4 different images on the screen, and timing shutters worn over the eyes to provide the correct image to each user's correct eye [15]

is beyond the scope of this chapter, and we refer the reader to relevant previous literature [40]. For the purpose of our taxonomy, we only consider the input space.

Input Space

The input space is defined as the physical location where the user can provide in-put. This property is important because it will impact the type of interaction techniques and usage metaphors which must be made available.

As we have seen, in the 2D realm, tabletops typically overlay input and display devices for direct-touch input. When working in 3D, this may no longer be feasible for three reasons: first, virtual objects may be perceived above the display plane, and thus cannot be "touched" by touching the display surface; second, display technologies may impair the ability to reach within the volume; and third, objects may simply not be within reach of the user. Clearly, the adaptation of the direct-touch input paradigm to the third dimension is not a simple one. The following lists input spaces which have been considered:

Direct 2D: The most common form of input with tabletop displays is direct 2D input, where the user can directly touch and interact with the displayed imagery (Fig. 12.11).

Indirect 2D: Indirect 2D input is useful when the display space is larger than the user's reach. Implementations include mapping a small local area of the display as the input space to the entire display surface [41], or by using a mouse or similar supplementary device [42, 43].

Direct Surface Constrained: In the spatially augmented reality systems where the virtual imagery is constrained to the surface of physical objects, interaction could also be constrained to those surfaces. For example, a user could add virtual paint to a physical object by using a physical brush tracked in 3D space [23].

Indirect Surface Constrained: Interaction can be surface constrained and indirect if an intermediate interaction surface is present. Such is the case with a

Fig. 12.11 Wu and Balakrishnan demonstrated direct-2D input in their room-planning application [8]

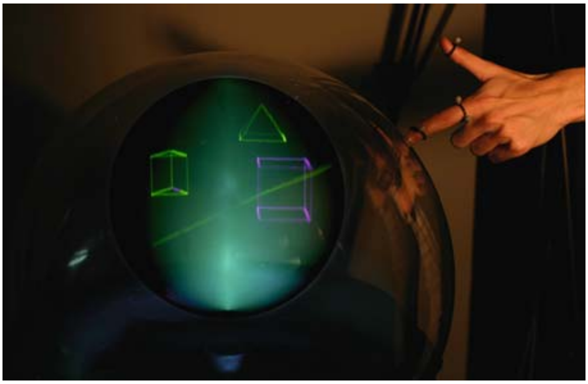

Fig. 12.12 Grossman et al.'s gestural interaction system for volumetric displays included input modes that were constrained to the surface of the device, but which mapped the 2D input space onto the volume within [34]

volumetric display, where the display enclosure can act as a touch sensitive surface [34] (Fig. 12.12).

Direct 3D: When the user can directly reach into the virtual imagery and grab objects in 3D space, the interaction is direct 3D. This is a common input metaphor in virtual reality environments, and is also possible in systems using stereo glasses.

Indirect 3D: In some virtual environments, the input is 3D, but indirect interaction techniques are provided. This is necessary when objects are out of the user's reach [44]. Indirect 3D interaction can also be used in volumetric displays, to overcome the physical surface between the user and displayed imagery [35].

Physical Properties

The last area of our taxonomy is the physical properties of the display. This is an important factor as it will affect how the user will interact with the display. Most relevant to the interactions is the physical properties of the actual work area, or perceived display space, and not the display hardware.

Physical Form

The physical form refers to the physical shape of the system. This property may affect possible input spaces, and required input mappings.

None: In head-mounted VR displays, the entire environment is virtual, so the work area has no physical form at all.

Enclosed: Most volumetric displays have an enclosed physical form, to protect the user form the mechanics of the display (Fig. 12.12). Various shapes of this enclosure have been proposed, including cuboid, conic, cylindrical, and hemispheric.

Table: In a typical tabletop setting, or a tabletop using stereo shutter-glasses, the physical form consists of the planar table surface.

Table with Proxies: In spatially augmented tabletops, the physical form is defined by the table and the location and shape of the addition physical proxies (Fig. 12.13).

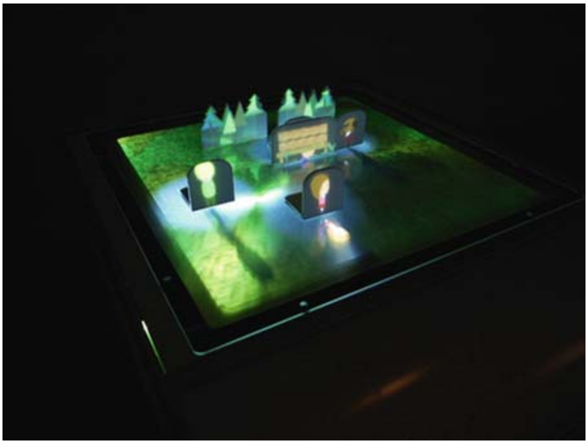

Fig. 12.13 Tabletscape plus provided physical properties which extended the display [27]

Physical Size

The other important factor relevant to physical properties is the size of the display. The affect of size has been discussed in the 2D tabletop literature [45], and we expect that similar issues will be present in 3D tabletop displays. We categorize sizes by what users can reach and what they can see, as these will be critical factors in the design of interfaces. While the definitions consider the areas within the reach of the user, it does not necessarily imply that the technology actually allows the user to reach into the display.

Personal: A personal sized 3D Tabletop display is small enough that the user can easily reach the entire display area.

Collaborative: With a collaborative sized display, a user can easily reach the center of the display. Such display sizes, for 2D tabletops, are generally meant for multiple users, so that between each user, the entire display space is accessible [45].

Large Scale: We define a large scale 3D tabletop display as being too big for a user to reach the center of the display. This means that even with multiple users, there will be areas inaccessible via direct touch interaction. However the display is small enough that users can easily see and interpret all areas of the displayed imagery.

Room Size: A room sized display would take up the entire space of a room. This means that there will be areas that the user cannot reach, and also areas that the user cannot easily see.

Taxonomy Application

One of the contributions of the taxonomy which we have presented is that it classifies the work which has been done into a cohesive framework. By examining where the existing technologies fall within this taxonomy, we can provide insights on what areas of research have been thoroughly explored, and what areas have been given less attention. Furthermore, by combining the various properties of the taxonomy in different ways, we can propose new and interesting 3D tabletop system implementations which have yet to be explored. Table 12.1 shows one such combination.

Table 12.1 Three parameters of our taxonomy: *Perceived Display Space*, *In-Put Space*, and *Actual Display Space*. *Light grey* cells are unexplored. *Dark grey* cells are impractical

Perceived display space		Actual display space			
	Input space	2D table	2D heads up	3D surface const.	3D volume
2D	2D planar	#1	#3	▨	▨
	Surface-const.	▨	▨	▨	▨
	Volumetric			▨	▨
3D surface	2D planar			#4	▨
	Surface const.			#5	▨
	Volumetric			#6	▨
3D volume	2D planar	[46, 14]	[21]	#7	#10
	Surface const.			#8	[34]
	Volumetric	#2	[21, 22]	#9	[35]

This particular arrangement of parameters allows us to focus on combinations of technologies, so that we might examine platforms for past and future development. As is immediately evident, some technologies have received more focus than others, while others have received almost no attention. A discussion of all areas is not within the scope of this paper: we will now review a few of the more compelling cells of this view of our taxonomy.

Planar Input to 2D Display (Cells 1, 2)

Cell 1 represents the large collection of 2D tabletop research which has been de-scribed previously [8–10], while cell 2 includes the multitude of 2D tabletop displays which were augmented with stereo viewing [14–17]. This has defined the baseline for research in 3D tabletops, though we hope to expand that focus.

Heads-Up Display of 2D (Cell 3)

Without a tabletop, this cell might describe various augmented reality projects. We are not aware, however, of any use of heads-up displays to augment a tabletop with 2D imagery. Although perhaps not as compelling as some of the 3D uses of this technology (from cell 2), heads-up displays for 2D tabletops might allow for interesting mixes of public and private information [8], and differentiate the view of each user [15], advantageous for reasons described by Matsuda et al. [47].

One system relevant to this area is PenLight, which augments physical paper with virtual imagery, projected from a miniature projector integrated into the pen itself [48]. This system was used to overlay 3D building information onto physical 2D blue prints. In its current implementation, the projected imagery is coplanar with the physical table. One interesting area to explore would be to instead project the imagery onto an intermediate surface, to distinguish between the physical and virtual display layers, or to display virtual cross sections in their true spatial locations.

Surface Constrained 3D (Cells 4–6)

Cells 5 and 6 include a number of projects which project imagery onto 3D surfaces. These projects include methods which limit input to moving objects around on the surface of the table [27] (cell 4), those which constrain it to the surfaces of 3D objects [24, 25] (cell 5), and those that allow unconstrained input [23, 26] (cell 6). The taxonomy allows for a quick distinction between these works, while also identifying an unexplored area (cell 4): the use of planar input to surface-constrained display areas. Such systems could provide interesting mappings between input and display spaces, such as manipulating objects by interacting with their shadows [49].

Stereo Spatial Augmentation (Cells 7–9)

These cells represent an as-of-yet unexplored use of 3D for tabletops. It describes a concept similar to Sandscape [25], Illuminating Clay [24], and Second Light [37] in that it would involve projecting onto the surface of 3D objects. However, with the addition of shutter glasses the system could present imagery which diverges from the structure of the physical proxies. With the current tabletop spatially augmented systems this is not possible. Such systems could be useful for scenarios where users view 3D models, and also want the ability to make minor adjustments to the structure.

Planar Input with Volumetric Displays (Cell 10)

This currently unexplored cell represents interacting with volumetric displays using traditional 2D input methods. This could be interesting to explore, since the input configuration could support standard desktop interactions which users are al-ready familiar with.

Interaction Issues and Design Guidelines

Due to the lack of a unified framework, previously interaction issues related to 3D tabletop systems have been discussed based on specific point designs and implementations. Similarly, the design decisions gone into the development 3D tabletop systems have been made on a one-by-one basis for each technological implementation. An intended contribution of our work is to be able to discuss interaction is-sues, and design guidelines for 3D tabletop systems at a higher level, independent of the specific implementation, based solely on where systems exist within the taxonomy. In this section, we present some of these generalized interaction issues and design guidelines.

Caveats in Increasing Perceived Display Space

In our taxonomy we discuss 3 possible perceived display spaces, with 3D volumetric being at highest level. The motivation to diverge from a 2D perceived display space is to improve the user's perception of the 3D environment, and in some cases to provide a more realistic simulation. While research has shown that introducing stereoscopic cues can improve a user's ability to carry out 3D tasks [38], designers should be careful before deciding upon the display configuration.

First, with the exception of autostereoscopic displays, providing a perceived 3D scene means introducing supplementary hardware, such as shutter glasses or head mounted displays. Such devices can be uncomfortable, reduce the ubiquity of the system (as they will no longer be walk-up-and-use), and can cause the user to lose the context of their surrounding environment or collaborators [18, 31].

Furthermore, when the perceived display space is inconsistent with the actual display space, the depth cues which the human brain receives become inconsistent. Most critical is the discrepancy between the accommodation and convergence cues, as this has been known to cause asthenopia in some users [50]. Symptoms associated with this condition include dizziness, headaches, nauseas, and eye fatigue.

A more subtle issue is that when the actual display space is 2D table con-strained and the perceived display space is 3D volumetric, there is actually a constraint on the perceived display space. Because the user is seeing pixels on the surface of the display, it would be impossible to perceive imagery that is above the user's line of sight to the back of the display. This means that the perceivable display space is actually triangular in shape – the further away the imagery is to the user, to less height it can have. As a result, such a configuration would not be very appropriate for applications where tall objects will appear, such as the architectural design of a high rise building.

The display configurations unaffected by these limitations are 2D tabletop systems, spatially augmented reality tabletop systems, and volumetric displays. These configurations should be considered if the designer foresees the discussed limitations as being problematic.

Losing Discrete Input and Tactile Feedback

Increasing the input space to 3D, whether it is direct or indirect, allows users to directly specify and manipulate objects in 3D space. However, there are a number of drawbacks of this input paradigm.

One problem is that discrete contact-to-surface events, which are typically used to trigger events in 2D tabletop interfaces, do not occur. As such, designers must provide interactions to execute discrete events. One possibility is to use free-hand gestures [51], such as a gun gesture to perform selections [34]. The alternative is to have the user hold an input device which has buttons that can be used to execute the discrete events.

Second, when interacting in midair, the user loses the tactile feedback present when interacting on 2D surfaces. This is problematic as sensory feedback is considered to be essential when interacting in 3D spaces [52]. Some explored solutions include bimanual input, physical proxies, and force feedback devices [52].

We refer the reader to Hinckley's survey paper on "spatial input" for a thorough discussion of other associated difficulties and possible solutions [52]. Due to these difficulties, designers should consider planar or surface constrained input, even if the technological implementation can support a 3D input space.

Mapping 2D Input to 3D Space

If planar or surface constrained input is being used, then the system needs a way to map two degrees-of-freedom interactions into 3D space. An exception is if no three degrees-of-freedom tasks are required in the application, such as the case for shallow depth interactions [10]. Otherwise, with only two degrees-of-freedom in-put, tasks such as moving an object to a point in 3D space must be carried out sequentially. A number of interactions have been developed to support 3D interactions with 2D input, such as three dimensional widgets [53]. Other possible approaches are to use supplementary input streams for added degrees-of-freedom, such as using a mouse scroll wheel [54], mouse tilt [55], or pressure [56] to define depth during interactions. Another way to increase the degrees-of-freedom is to use bimanual interactions [57] and multi-finger gestures [46].

Indirect Interactions May Be Required

While there are tradeoffs to using direct and indirect interactions in 3D tabletop applications, there are some cases where we would strongly suggest that indirect interactions be provided. Obviously if the input space is indirect, then indirect interaction techniques must be provided. Furthermore, when the physical form of the system is enclosed, then the interaction space must be indirect. Lastly, when the physical size is large scale or room size, then indirect interactions are required to make all areas of the display accessible.

One possible indirect interaction technique is to use a virtual cursor, which has a positional offset form the user's hand or handheld input device [44]. Another technique commonly used in VR applications is a ray cursor, which acts like a virtual laser pointer being emitted from the user's hand [58]. This approach has also been used in 2D tabletop systems [43], and studied within volumetric displays [35]. The use of physically "flicking" objects to move them to inaccessible areas has also been investigated [41].

Providing Navigation and Visual Aids

The transition from 2D to 3D necessitates a series of changes in the way navigation is handled and visualized. For example, in systems which lack viewpoint correlation of 3D imagery, a mechanism will be required to allow for the viewpoint to be changed. Conversely, in those systems which do provide some correlation of viewpoint to head position, visualization of the automatic change of viewpoint may be required to overcome orientation effects.

This is equally true as the perceived or actual space grows beyond the tabletop: in room sized displays, mechanisms to allow the user to see distant imagery may be required.

Lessons from 2D

Each of the above guidelines were derived through categorization and examination of efforts already expended in 3D tabletop systems. Here we describe lessons al-ready learned by researchers of traditional tabletops, which may need to be re-examined when moving to 3D.

Common, Shared Display and Input Area

Various research efforts have uncovered behaviours of both individuals and groups using tables and interacting with either physical or virtual objects. These include user territoriality [59], effects of group and table size [45], closeness [47], and the use of orientation for communication [16]. As tables move to 3D, several of these issues may increase in prominence, and new issues may arise.

Varied Point of View

With users seated around all sides of a tabletop, each participant receives a distinctly different view of information on the display. As such, traditional desktop interfaces, which assume a particular orientation, are clearly inappropriate for these displays. A great deal of research has gone into the effects of orientation on group interaction [59–62] and perception [63–65], and interfaces to help overcome or exploit these issues [63, 66]. Naturally, with 3D tabletops, this problem is much more severe, since the rotation of objects can be in any of three orientations, and in fact faces of 3D objects may be completely invisible to some users. Early work describing this issue with text readability found interesting results [67], but further is required.

Conclusions

In this chapter, we have introduced a taxonomy of 3D tabletop systems. This taxonomy categorizes 3D tabletops based on their display, input and physical proper-ties. A contribution of this taxonomy is that it allows us to organize previous research into a single high-level framework. Furthermore, it allows us to identify combinations of the discussed properties which have yet to be explored.

Evident from the large body of work in 3D tabletops is that they are a compelling platform for future development. It is our hope that, through the creation of the taxonomy, we will inspire and aid further development in this domain.

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