PaperLens: Advanced Magic Lens Interaction Above the Tabletop

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ABSTRACT

In order to improve the three-dimensional (3D) exploration of virtual spaces above a tabletop, we developed a set of navigation techniques using a handheld magic lens. These techniques allow for an intuitive interaction with two-dimensional and 3D information spaces, for which we contribute a classification into *volumetric, layered, zoomable,* and *temporal spaces*. The proposed *PaperLens* system uses a tracked sheet of paper to navigate these spaces with regard to the Z-dimension (height above the tabletop). A formative user study provided valuable feedback for the improvement of the *PaperLens* system with respect to layer interaction and navigation. In particular, the problem of keeping the focus on selected layers was addressed. We also propose additional vertical displays in order to provide further contextual clues.

Keywords

Interaction techniques, spatially aware displays, multi-layer interaction, three-dimensional space, tangible interaction

INTRODUCTION

The past years have seen rapid improvements in research and technology for large displays and interactive surfaces, such as tabletops, and associated natural interaction techniques using hand gestures, multi-touch, or tangibles. The three-dimensional (3D) space above interactive tabletops has been used rather scarcely, since interaction techniques usually focus on the surface itself. Due to continuously growing information spaces, data filtering and exploration tasks become more and more challenging. In this respect, the concept of Magic Lenses [1] as a detail and context technique is a promising solution. This idea has been extended to tangible displays (e.g. [2]) for the application with tabletop environments. However, such systems usually only focus on certain aspects of spatial data exploration, rarely use the volume above a display and often employ complicated, expensive or heavy hardware (e.g. tablet PCs).

In order to improve the aforementioned issues, we developed *PaperLens* as a lightweight handheld display

solution allowing the exploration of virtual information spaces above a tabletop. The exploration space above the surface serves as a virtual volume for various types of applications. Depending on the nature of the displayed data and the utilization of the Z-axis, we distinguish between a *volumetric, layered, zoomable,* and *temporal information space*. By moving a tracked sheet of paper through the interaction volume, the displayed content adapts according to the current position with regard to the contextual tabletop display (see Figure 1 and 2). A formative user study helped us in improving our solution.

Although the idea of tangible magic lenses and the interaction above a surface is not new, novel technological solutions such as [7] and [6] suggest the strong potential of this research area. In summary, our main contributions are (I) a set of improved navigation techniques and aids that are motivated by a user study, (II) the introduction of layered and temporal information spaces in combination with mobile lenses, (III) a systematic classification of different data types and how they might be effectively explored with movable lenses, and (IV) a technical solution for a lightweight and untethered tangible lens in a tabletop environment.

The remaining paper is organized as follows. After a short discussion of related work, we introduce the *PaperLens* concept and describe how it can be utilized to explore different types of information spaces in various application scenarios. In the next section, a formative user study and corresponding findings are reported. Improved navigation techniques based on this study are discussed thereafter. Finally, our technical solution is introduced, followed by conclusions and an outlook to future work.

RELATED WORK

The deployment of spatially aware handheld devices in combination with large displays has been of interest for many years now. The Magic Lens concept [1] for presenting customized views of an underlying application has been frequently used in this context. Various tangible magic lens prototypes have been developed for spatially aware displays, which differ in their implementation and application. Thereby, a general distinction can be made between active (screens/displays) and passive lenses.

One of the first active lenses for ubiquitous usage has been proposed by Fitzmaurice, who presented a spatially aware palmtop computer for exploring 3D-situated information

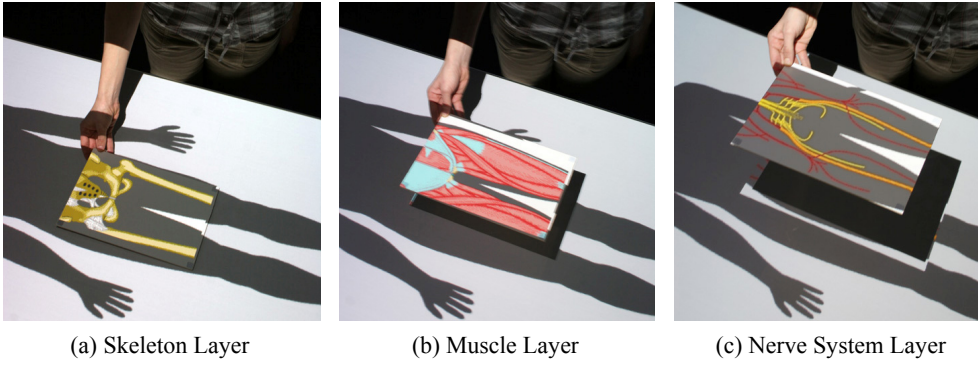| (a) Skeleton Layer | (b) Muscle Layer | (c) Nerve System Layer |

Figure 1: Initial prototype for the layered information space using a top-projected tabletop (see shadows). Depending on the lens' height, different layers are presented.

Figure 2: General setup of the top-projected PaperLens.

spaces for revealing virtual information associated with real items [3]. Based on this idea, Small and Ishii present two designs for scrolling large paintings and reading portable newspapers [16]. In order to zoom content in and out, the display needs to be moved away or closer to the user. Yee also extends the work from Fitzmaurice by proposing the Peephole Display [22] for exploring 2D virtual workspaces, such as geographical maps and calendars. Sanneblad and Holmquist use small active displays (tablet PCs) in combination with large screens for navigating through 2D graphical user interfaces (geographical maps) and for providing detail and annotation capabilities [15].

Compared to active displays, such as UMPCs or tablet PCs, paper displays are more lightweight, flexible, robust and variable in shape. Paper displays can be used as passive lenses, since they simply act as a projection screen. A first paper display was developed for the *DigitalDesk* [21] and used a top-projection to show a user interface (e.g. a virtual calculator) on a piece of paper. Further top-projected displays have been developed for PaperWindows [5] and by Lee et al. [11].

Recent bottom-projected approaches, such as UlteriorScape [7] and SecondLight [6], usually comprise a more technical solution. UlteriorScape is a combination of a tabletop environment with additional objects as projection screens. The system has been used for filtering photographs, arranging characters in a theater application and displaying different languages based on the users' viewpoints. SecondLight by Izadi et al. [6] is a rear projection-vision system that quickly switches between projections on the entire surface and the tangible magic lens. Similar to the idea from Small and Ishii, Izadi et al. propose moving the lens towards or away for zooming, but this time with regard to a multi-touch tabletop surface. Another example for a technically complex system has recently been presented by Koike, Nishikawa and Fukuchi introducing transparent 2D markers on an LCD tabletop system [9].

The metaDESK system by Ullmer and Ishii [19], which contains both an active and a passive lens, has been used for zooming in a 3D geospace. Another example for deploying both active and passive lenses has been presented by Brown and Hua [2], who use an active embedded and a passive handheld lens. Two applications
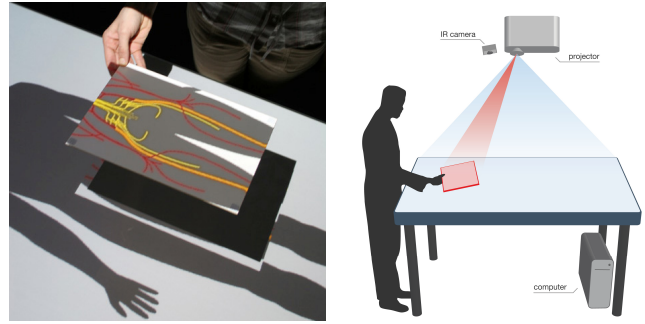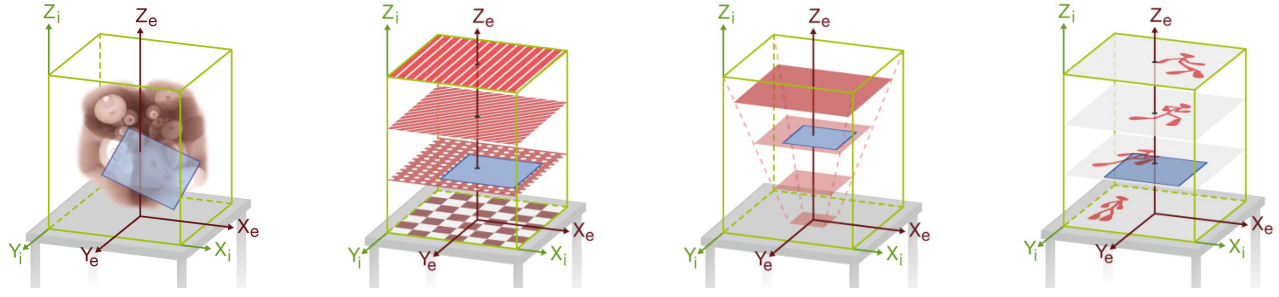
are presented for using this system in the area of urban planning (exploring a virtual city) and medical training in a 3D augmented virtual environment. Further examples for using magic lenses in Augmented Reality (AR) environments are often based on the concept of 3D magic lenses [20], as applied, for instance, by Looser et al. [12]. Typically for most AR approaches, 3D objects augmented to real environments are the focus of attention; additional surface displays are only rarely used.

After all, a range of different types of spatially aware displays and corresponding applications exists. However, many of the previous approaches (especially with rear-projected displays) are complicated and expensive technical setups (e.g. [6] and [7]). Since we aim at a system that is as simple and flexible as possible, *PaperLens* is designed as a technology-reduced, top-projected paper display.

As the reported work indicates, tangible magic lenses have already been used for several applications, but often only to demonstrate the potential of a technical solution which was the central contribution. However, the potential for the manifold application possibilities of such devices has hardly been exhausted and requires further systematical examination. This applies particularly to the utilization of the space *above* a reference surface to provide a rich set of natural 3D exploration techniques. One example for using this space has been presented by Subramanian, Aliakseyeu and Lucero for pen interaction above a tabletop [18]. However, this approach focuses only on multiple layers and pen interaction, while we also look at exploring continuous information spaces with lenses.

EXPLORING VIRTUAL SPACES

The *PaperLens* approach, first proposed in [17], is a simple and affordable tangible magic lens. It allows the user to explore different types of virtual data spaces – which we subsume as the *exploration space* $(X_eY_eZ_e)$ – by moving a thin board through the *interaction space* $(X_iY_iZ_i)$. This space describes the continuous 3D real-world volume above a horizontal reference surface (tabletop display) with the Z-axis defined by the direction perpendicular to its surface. We identify four classes of distinguishable exploration spaces: *volumetric*, *layered, zoomable,* and *temporal information spaces.* The PaperLens enables the exploration of such spaces by employing just a few basic

(a) Volumetric Information Space　(b) Layered Information Space　(c) Zoomable Information Space　(d) Temporal Information Space

Figure 3: By moving the PaperLens (blue rectangle) through the interaction space ($X_iY_iZ_i$, in green) users can study the four types of exploration spaces ($X_eY_eZ_e$, in red).

navigation techniques: *depth translation* (change of Z_i), *XY-translation* (change of X_iY_i) and *tilting* (rotation in $X_iY_iZ_i$ space).

In the remainder of this section, properties of these spaces along with application scenarios and prototypes are systematically discussed.

Volumetric Information Space

A *volumetric information space* can be described as a set of 3D samples or voxels (see Figure 3a). It is continuous in all three dimensions and allows for a direct linear one-to-one mapping between ($X_iY_iZ_i$) and ($X_eY_eZ_e$). This is similar to the work by Hirota and Saeki [8] and Konieczny et al. [10], even though both do not make use of a tabletop. Thus, depth- and XY-translation can be mapped to simple shifts of height (Z_i) and movements in X_iY_i , while tilting provides a natural method for "slicing". In this manner, the *PaperLens* acts as a "window" into virtual volumes that can be freely moved and rotated in all three dimensions and angles (6DOF).

Application Scenarios

Typical volumetric datasets are from medical or geological domains, such as Computer Tomography (CT) or seismic data that can be explored with *PaperLens*. Thus, such a system could, for example, ease pre-operational planning. A tabletop in a doctor's office may help in communicating diagnostic findings to patients or discussing them with colleagues (compare to the work by Brown and Hua [2]). In another scenario, *PaperLenses* may aid geologists in detecting oil or gas reservoirs similar to the interactive visualizations by Ropinski and Hinrichs [14], who present a virtual 3D magic lens for examining subsurface information.

Prototype

Figure 4a shows a prototype that allows users to scan through 3D volumetric datasets of human bodies by moving the *PaperLens* above a silhouette of a human. For this prototype, we equally stacked 45 images of 740×416 pixel resolution to fill the 45cm of available height (lens tilting was not supported here). In a second prototype shown in Figure 4b, we mapped an MRT scan of a human head of 256 × 256 × 192 pixel resolution onto the physical space of 25cm × 25cm × 25cm. Here, users could arbitrarily slice the data in every direction and orientation.
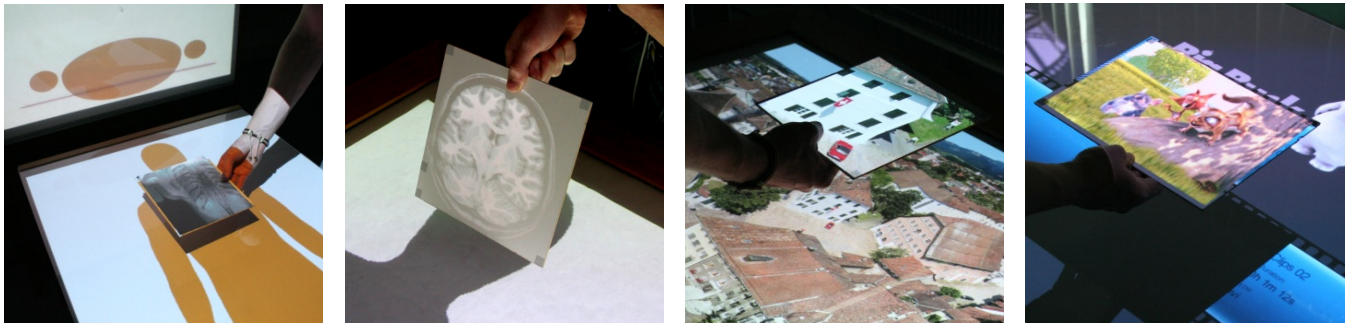
Layered Information Space

We define *layered information spaces* as sets of two-dimensional data with each data layer representing a unique feature of a model. Usually, this data is continuous within a 2D plane enabling a direct linear mapping from X_iY_i - space onto the X_eY_e - space (see Figure 3b). In order to map Z_i onto Z_e, the Z_e -axis can be divided into discreet intervals that are later associated with single information layers. Thus, a layered information "volume" is constructed, with each layer covering a distinct "height" in the exploration space. Due to this design, users can easily navigate through or change layers by using the same interaction paradigm: moving the lens in the physical space above the tabletop. This means, after selecting a layer of interest by lifting/lowering the lens (depth translation) they can intuitively explore this layer by horizontally moving the lens (XY-translation).

Application Scenarios

We see the main advantages of mobile lenses with layered information spaces in linking detail with context and collaborative work. As compared to just flipping through layers on a single tabletop display, our system allows to simultaneously display two or more layers (depending on the number of lenses). Of course, layer selection could be accomplished entirely by using buttons or gestures on the tabletop. However, we believe that the mobile lens itself is a valuable tool for interaction that can help preventing users to switch between different modes of interaction too frequently. Therefore, we suggest combining conventional interaction techniques, such as buttons on the lens, with the depth-based interaction metaphor of the PaperLens. This might, for example, be useful for layered menus that are stacked above the tabletop, similar to [18] but with a direct visual feedback directly on the lens. These ideas need to be explored more carefully in future work.

In geographic information systems users may use the lens to navigate through different types of raster data (e.g. satellite pictures) and vector data (e.g. street maps or terrain data). Layers may also represent different types of filters or rendering styles for an underlying model or dataset (e.g. a photograph) that might be explored by moving the lens up or down.

(a) Volumetric Information Space (additional vertical display) (b) Volumetric Information Space (back-projected, no lens shadow) (c) Zoomable Information Space (slices of arbitrary orientation) (d) Temporal Information Space (top-projection, lens shadow)

Figure 4: Various prototypes of the PaperLens demonstrating several exploration spaces.

Prototype

In Figure 1, a prototype is shown that allows medical students to examine four information layers: the skeletal, muscular, blood, and nervous systems of the human body. Here, each layer is of equal height (approx. 11cm). They can be examined by lifting/lowering the lens (layer selection) or by horizontally moving the lens (navigation within a layer).

Zoomable Information Space

With *zoomable information spaces*, large continuous 2D information worlds (e.g. gigapixel images or maps) can be represented that extend far beyond the tabletop in their original size. In this context, zooming and panning usually play an essential role. The concept of space-scale diagrams [4] is a possible way to describe such spaces. It employs a pyramidal representation of the information world with the pyramid's height representing the level of detail/zoom. This enables the direct mapping from $(X_iY_iZ_i)$-space onto the $(X_eY_eZ_e)$-space in such a way that the pyramid's Z_e-axis is aligned with the Z_i-axis (see Figure 3c).

By this means, depth translation can be interpreted as a scaling function that allows users to zoom into the information world by lifting the lens. This metaphor is similar to the real world experience of many users who bring objects of interest closer to their eyes in order to examine them in more detail. At the same time, panning operations can be expressed by means of XY-translation.

Application Scenarios

A typical application for zoomable information spaces is the exploration of high resolution imagery, such as satellite images. By lifting the lens, more details are displayed. In contrast, the opposite approach is also possible. Similar to a magnifying glass, a user could obtain more details by moving the lens closer to the reference surface, which could be achieved by inverting the pyramidal representation (studying this approach lies beyond the scope of this paper and will be left for future work). Besides the broad application of geometric zooming, the zoomable information space could also be combined with the idea of semantic zooming or facet browsing (e.g., of media collections). Here, additional semantic zoom levels might be represented by supplemental layers similar to the concept of layered information spaces.

Prototype

Figure 4c shows a prototype that allows the exploration of zoomable information spaces. In this scenario, further details are revealed from high resolution photographs when the user moves the lens up. In doing so, the user can linearly increase the zoom level up to a factor of 15 at a height of 45cm above the tabletop.

Temporal Information Space

Temporal information spaces are a concept for describing 2D time-dependent data, such as video sequences. As illustrated in Figure 3d, this is achieved by virtually stacking layers of time (or time frames) one upon the other, in order to create a volumetric description $(X_eY_eZ_e)$ of the temporal data with the Z_e-axis representing the time or "state". This volume can then easily be mapped onto the interaction space $(X_iY_iZ_i)$, which allows users to navigate through time by lifting/lowering the lens (depth-translation). Additionally, the tabletop display can supply a collection of several temporal data sets (e.g. video snippets) that are "scattered" over the display (each one represented by a still image). This would enable the user to select a piece of temporal data by simply moving the lens over it (XY-translation).

Application Scenarios

Temporal information spaces cover a broad spectrum. Depending on the application scenario, the user could be interested in abrupt changes over time (e.g. surveillance videos) which might be detected more easily by lifting or lowering the lens. This may also comprise state changes in more abstract data such as weather alterations over time.

In general, users can perform a wide range of operations with the PaperLens when examining temporal spaces. They can "watch" a sequence by simply raising the lens, they can easily go backward and forward by lowering and lifting the lens, they can even do it quickly or slowly (slow motion) depending on how fast they move the lens up or down and they can look at a particular still image by holding the lens stable. Obviously, the PaperLens will most likely never be used to "watch" a whole movie. We rather see its strength in its simple-to-understand but powerful design that allows for a more coarse-grained interaction in comparison to e.g. using sliders on a tabletop, which require finer motor skills.

However, with all these operations available, we also see a potential in the domain of video editing. This could be achieved by introducing further input devices, such as buttons on the lens allowing users to mark start and end times of a sequence. Furthermore, we suggest introducing "lens gestures", e.g. "grabbing" a video snippet with the lens and then "sliding it down" at a different position on the tabletop. By doing so, a complete "film" might be composed by arranging video snippets on the tabletop display. However, the effectiveness of these suggestions needs to be studied further.

Prototype

In Figure 4d, a prototypic video snippet browser is shown. For this purpose, four short video sequences (represented as still images) are arranged on the tabletop display that can be selected and "watched" as described earlier. Here, each video snippet consists of up to 150 frames (6 sec) that are mapped onto an interaction volume's height of 45cm.

USER STUDY

After having introduced the four basic exploration spaces along with application scenarios and prototypes, this section describes a formative user study. It has been conducted for gathering initial feedback about working with the *PaperLens*. As part of an iterative process, a prototype has been tested first to provide insight for more complex solutions. Besides an overall evaluation of potential usability issues, we aimed at a deeper understanding of the convenience and reliability to navigate through the different information spaces. This also included the effort of users to get acquainted with this system. Since the study was based on an early *PaperLens* prototype, only three information spaces were considered here: the *volumetric, layered,* and *zoomable* space.

Participants

Twelve unpaid, right-handed participants from our institution (age between 25 and 35, three female) volunteered for the study. Some of them worked in the domain of medical visualization or computer graphics before, but only three of them had prior experiences with spatially aware displays or interactive tabletops.

Apparatus and Tasks

The usability study was based on early *PaperLens* prototypes that used a three corner marker design which did not allow for tracking of tilted lenses. These prototypes (see previous section) were modified prior to the tests to provide specific search tasks to the subjects. In the MRT scan of a human torso (volumetric space) two tumors, which were represented by blue areas, were added (one task). For the layered information space, five red and four green dots were placed on the skeleton and blood system layers, which the participants were asked to count (two tasks). In the zoomable information space, the participants had to detect two particular details in a large image, which were unrecognizable without the *PaperLens* (two tasks). We used a within-subjects design for the user study and counterbalanced the order of tasks.

Procedure

At the beginning of the test, the *PaperLens* was placed in a neutral position on the tabletop surface. Prior to collecting data, the study supervisor briefly introduced the *PaperLens* as a "spatially aware device that enables the natural interaction with virtual spaces". Thereby, neither the exact nature of the spaces, nor particular interaction techniques were explained. Thus, the subjects had to discover for themselves how to interact with the system. After the introduction, participants were asked to complete five tasks as described in the previous section. After each task, participants filled out a small questionnaire about their subjective impressions regarding the difficulty of the task (11 questions in total). Finally, a questionnaire about demographic and computer usage information as well as subjective overall impressions had to be completed by each participant (6 questions). For this purpose, we used a 7-point Likert scale ranging from strongly disagree (-3) to strongly agree (3). Additionally, we videotaped each session and took notes of the think-aloud data.

Results and Discussions

The given tasks were successfully accomplished by all 12 participants almost without errors. Since no instructions on how to use the system have been provided, we assume that *PaperLens* suggests an intuitive use. This finding is further confirmed by the positive feedback from the questionnaire, where participants agreed to the statements that "it was easy to learn the system" (Mean (M)=2.83, Standard Deviation (SD)=0.39) and "it was easy to use the system" (M=2.33, SD=0.49).

Layered Information Spaces

The main point of criticism was the interaction with layered spaces. Participants commented that it was easy for them to maintain the focus in a layer close to the tabletop (M=2.25, SD=0.62), but difficult in higher layers (M=1.58, SD=1.08). This applied in particular when moving the *PaperLens* over a longer XY-distance. Some users (n=3) pointed out that the selected layer should be "thicker than other layers to make it easier to stay inside". Various subjects (n=7) complained about abrupt and unpredictable changes of layers. Several users (n=4) asked for a blending between layers. Three participants suggested providing additional navigational aids, such as a height indicator. Our observations also provide some evidence that most users perceive layers much thinner than they are in reality, which applies particularly to upper layers. However, further experiments are necessary to confirm our findings. Later in this paper, a set of navigation aids is presented that aims at tackling some of the issues discussed here.

Tilting the PaperLens

The usability study showed that participants found it more natural to hold the *PaperLens* tilted. This was predictable for the volumetric space for which almost all participants (n=10) tried to slightly tilt the lens towards themselves in order to slice the volume. However, this also applied to the layered and zoomable space, where several users (n=6) tilted the *PaperLens,* because they found it to be "more convenient", especially in greater heights.

As reported by other researchers (e.g. [2] and [18]), some participants (n=4) had minor difficulties in holding the lens stable while exploring the zoomable space. However, three of them commented that they did not perceive this as a big annoyance, which is probably due to the continuous character of this space. Aside from that, a few participants (n=2) asked for a bigger *PaperLens* for scanning the volumetric space.

IMPROVED NAVIGATION TECHNIQUES

In this section, we will discuss navigation techniques, partly as being improvements of our initial *PaperLens* prototypes.

Navigating through Information Layers

We will start by discussing techniques that tackle issues with layered information spaces as revealed by the formative user study. Basically, these were problems of keeping the focus and of abrupt layer changes with layers of constant height.

In order to make it easier for the user to stay in focus, we virtually double the height of the currently selected layer. This is achieved by considering half of the neighboring layers as a blending area (see right part of Figure 5). When the *PaperLens* passes an original layer border (dotted lines) and thus enters a blending area, the content of both layers will be linearly interpolated and displayed on the lens' display. This way, users get an indication that they are about to leave the currently selected layer. Once the PaperLens crosses the extended border (dashed line), the current layer fades out completely in favor of the new one. There are cases, where blending of layers is not appropriate, e.g. for alternative information layers. For this case we basically suggest the same concept of increasing the current layer's height, but without any blending effect (see middle part of Figure 5). Since users seem to perceive layers thinner than they are in reality, we additionally suggest to use a non-linear stacking of layers (see left part of Figure 5). Another promising approach might be the drifting correction suggested by Subramanian *et al.* [18].

Navigational Aids

When interacting with the *PaperLens*, the user needs to be aware of the position and orientation of the lens within the exploration space. In order to avoid that users get lost, we suggest employing four navigational aids. First of all, the *tabletop display* provides context information of the underlying data (e.g. geographical map or outline of a human body). Next, a *second perpendicular display* can be used for presenting a side view or cut of the exploration
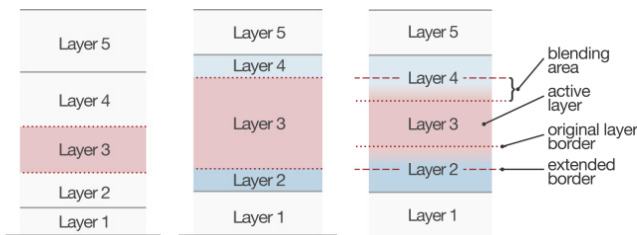

Figure 5: Layer arrangements (from left to right): increasing layer height, active layer expansion, active layer blending

space (see Figure 4a). To further improve a user's orientation, we show the *vertical and horizontal projection (outline) of the lens* on one or both displays. See examples of these outlines in Figure 4a and 6c. This technique is especially useful for back-projected tabletops, where lenses do not cast shadows, like with the example in Figure 4c. As a fourth navigational aid the display of the lens is augmented with a *height indicator* providing visual feedback for the minimum, maximum, and current height of the lens. Thereby, human capabilities and eye sight suggest an overall maximum height of the lens of 35 to 45 cm above the tabletop. In addition, the height indicator may also be used to indicate distinct layers (see Figure 6c).

Another more general problem with handheld devices is fatigue. Although we did not directly encounter this during our studies, we suggest a "freeze" mode, where the current view does not change when the lens is moved so that it can be brought to a more convenient resting position.

Tilting the PaperLens

As suggested by the user study, tilting is a fundamental requirement for the interaction with the *PaperLens*. In the following, we will briefly discuss, how each of the exploration spaces can benefit from it. For volumetric spaces, tilting is essential if arbitrary slices of the 3D data (at an oblique angle) shall be displayed on the lens, thus making tilting a vital part of the navigation technique. In contrast, for the other three spaces, tilting does not have such an intrinsic meaning, but rather helps improving ergonomics. Here, tilting is primarily used for getting a better view angle at the lens. Thereby, a perspective correction ensures that the image stays virtually undistorted on the lens.

TECHNICAL APPROACH

For the implementation of the *PaperLens* we have chosen a passive display approach similar to the one suggested by Holman et al. [5]. The general setup consists of a top projector and an infrared camera that are both mounted on the room's ceiling (see Figure 2). The *PaperLens* – a piece of press board with IR-reflecting markers attached to it – is tracked via the camera. Once the PaperLens' position and orientation is known, the top projector can be used to project images onto the lens' surface (as long as it resides within the projection volume). During our studies, we have augmented this setup with further displays and came up with a couple of display configurations that are described in the following. In this section, we will also discuss other implementation issues, such as marker design and tracking, lens design, as well as perspective correction.

Display Configurations

In all setups, we used a horizontal tabletop as the basic requirement serving both as a reference surface and a visual context. In addition, we tested the following options:

Top-projected tabletop and lens

For the first prototype, a passive display approach was chosen for the tabletop, i.e. the ceiling-mounted top projector was also responsible for projecting onto the tabletop surface. Although this approach produces shadows
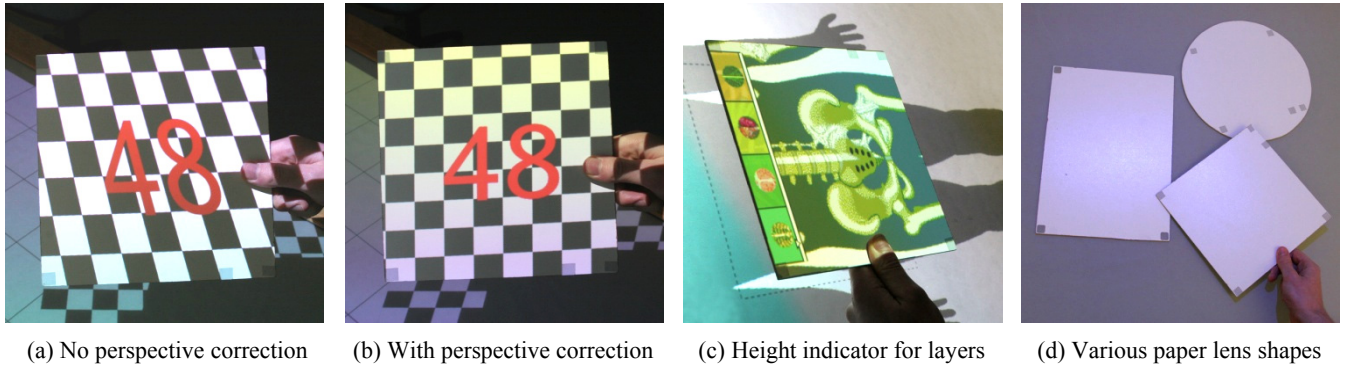
| (a) No perspective correction | (b) With perspective correction | (c) Height indicator for layers | (d) Various paper lens shapes |

Figure 6: Perspective correction in the PaperLens system, height indicator projected on lens, and lens designs

caused by the lens, it has proven to be a simple but appropriate solution.

Back-projected Tabletop, top-projected Lens

In order to avoid shadows, we later combined the top-projected PaperLens with a back-projected tabletop. This is essential if the projected outline of a lens shall be displayed on the tabletop (see Figure 6c).

Vertical Display

We also combined the horizontal tabletop with a secondary vertical display. This provides additional contextual clues for vertical aspects of an exploration space (e.g. cuts) that change dynamically depending on the lens' position (see Figure 4a). Communication between displays is organized as a client/server solution using our own framework.

Marker Design and Tracking

For lens tracking, an OptiTrack FLEX V100 IR camera at 50Hz with a 640x480 pixel resolution is used. IR-reflecting markers of size 5x5mm were glued onto the corners of a rectangular *PaperLens*. For simplicity, we first experimented with a *three corner design*. Here, the height of the lens was computed by taking the projected triangular-shaped area into consideration that was spanned by the markers and changes linearly depending on the height of the lens. Naturally, this design only works well under the condition that lenses remain parallel to the tabletop surface, which prevents the correct tracking of tilted lenses. To improve on that, a *four corner design* was implemented by adding a marker to the fourth corner. This allowed us to employ ARToolKit's [23] internal detection code for the determination of the lens' exact position and orientation. In order to ensure rotation invariance (up vector of lens' display), we later introduced a fifth marker (see Figure 6d). Furthermore, an averaging of recorded marker positions diminished unintentional jittering.

Lens Design

Due to the passive display approach and the simple and flexible marker design, it only takes small efforts to produce lenses in different sizes and shapes. For our implementation we have built several prototypes that have all been made of press board with IR-reflecting markers attached to them (see Figure 6d). Besides some variants of square- or rectangular-shaped prototypes with different sizes, we also used a circular-shaped lens that aims at mimicking the traditional shape of a magnifying glass.

Perspective Correction

To compensate for projection errors, which occur if top-projected lenses are tilted (see Figure 6a), we emulate the physical space above the tabletop (projector and lens) with OpenGL. This is done in such a way that the OpenGL camera resides at the position/orientation of the top projector and the physical lens (shape, position and orientation) is mimicked by a textured polygon. In this way, the OpenGL camera always "sees" the lens and its content in the correct perspective (see Figure 6b).

However, the passive lens' top projector-based approach is naturally limited to tilting angles up to 45°. Otherwise, pixel distortions become dominant and the information density on the lens decreases too much. Although active lenses, such as OLEDs, would entirely solve this problem, our tech-free and flexible PaperLenses are well suited for many application scenarios.

CONCLUSION AND FUTURE WORK

In this work, we have introduced *PaperLens*, a lightweight, flexible, shape-variable and robust display solution. This spatially aware handheld lens suggests a set of natural interaction techniques for the spatial exploration of virtual information spaces in the real-world space above a tabletop. For that, we identified four basic types of explorable data spaces: the *volumetric, layered, zoomable,* and *temporal information space*. The *PaperLens* serves as a window into these virtual spaces. Thereby, we focused on employing the Z-dimension (height above the tabletop) in order to develop a set of natural lens navigation techniques. We have implemented prototypes for all of the four classes of exploration spaces. In a formative user study, three of these spaces were examined and valuable insights were gained. As a consequence, *PaperLens* was enhanced with additional navigational aids, tilting, and further navigation techniques for the layered space. These aids and associated interaction techniques still need to be evaluated more deeply.

For future work, we plan a follow-up study on the suggested layer selection techniques and navigational aids as well as a comparison with conventional techniques, such as multi-touch. Beyond that, we are particularly interested in further studying specific interaction techniques for the selection and manipulation of data. We also intend to let domain experts evaluate the applications described in this

paper in order to determine whether and under which conditions the techniques will be beneficial. In addition, it will be interesting to investigate the use of multiple lenses for collaborative work. Beyond the exploration of information spaces, we also aim at investigating the applicability of *PaperLens* for data editing purposes, e.g. video editing. This will be achieved by introducing additional input modalities such as lens buttons or lens gestures.

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REFERENCES

1. E. A. Bier, M. C. Stone, K. Pier, W. Buxton, and T. D. Derose. Toolglass and magic lenses: The see-through interface, In *Proc. of SIGGRAPH '93,* 1993, pp. 73-80.

2. L. D. Brown and H. Hua, "Magic lenses for augmented virtual environments", *IEEE Computer. Graphics. Applications.* 26(4), 2006, pp. 64-73.

3. G. W. Fitzmaurice, "Situated information spaces and spatially aware palmtop computers", Commun. ACM, 36(7), 1993, pp. 39-49.

4. G. W. Furnas and B. B. Bederson, "Space-Scale Diagrams: Understanding Multiscale Interfaces", *In Proc. of CHI '95*, ACM Press, New York, USA, 1995, pp. 234-241.

5. D. Holman, R. Vertegaal, M. Altosaar, N. Troje, and D. Johns, "Paper Windows: Interaction Techniques for Digital Paper", *In Proc. of CHI '05*, ACM, New York, NY, USA, 2005, pp. 591-599.

6. S. Izadi, S. Hodges, S. Taylor, D. Rosenfeld, N. Villar, A. Butler, and J. Westhues, "Going Beyond the Display: A Surface Technology with an Electronically Switchable Diffuser", *In Proc. of UIST '08,* ACM, New York, USA, 2008, pp. 269-278.

7. Y. Kakehi and T. Naemura, "UlteriorScape: Interactive optical superimposition on a view-dependent tabletop display", *In Proc. of 3rd IEEE International Workshop on Horizontal Interactive Human Computer Systems TABLETOP 2008*, 2008, pp. 189-192.

8. K. Hirota, Y. Saeki, "Cross-section Projector: Interactive and Intuitive Presentation of 3D Volume Data using a Handheld Screen", In *Proc. of the IEEE Symposium on 3D User Interfaces 2007*, 2007.

9. H. Koike, W. Nishikawa and K. Fukuchi, "Transparent 2-D markers on an LCD tabletop system", In *Proc. of CHI '09*, ACM, NY, USA, 2009, pp. 163-172.

10. J. Konieczny, C. Shimizu, G. W. Meyer and D. Colucci, "A Handheld Flexible Display System", In *Proc. of VIS2005*, Minneapolis, USA, 2005, pp. 75-81.

11. J. C. Lee, S. E. Hudson, J. W. Summet, and P. H. Dietz, "Moveable interactive projected displays using projector based tracking", In *Proc. of UIST '05*, ACM, New York, NY, USA, 2005, pp. 63-72.

12. J. Looser, R. Grasset and M. Billinghurst, "A 3D Flexible and Tangible Magic Lens in Augmented Reality", In *Proceedings of ISMAR '07*, IEEE Computer Society, Washington, DC, USA, 2007.

13. J. Oh and H. Hua, "User evaluations on form factors of tangible magic lenses", In *Proc. of ISMAR'06,* Washington, DC, 2006, pp. 23-32.

14. T. Ropinski and K. Hinrichs, "Interactive Volume Visualization Techniques for Subsurface Data", In *Proc. of VISual05*, Amsterdam, Netherlands, 2005, pp. 121-131.

15. J. Sanneblad and L. E. Holmquist, "Ubiquitous graphics: combining hand-held and wall-size displays to interact with large images", In *Proc. of AVI '06,* ACM, New York, NY, USA, 2006, pp. 373-377.

16. D. Small, and H. Ishii, "Design of spatially aware graspable displays", *In CHI '97: Extended abstracts on Human factors in computing* systems, ACM, Atlanta, Georgia, USA, 1997, pp. 367-368.

17. M. Spindler, J. Sieber, and R. Dachselt, "Using Spatially Aware Tangible Displays for Exploring Virtual Spaces". In *Proceedings of Mensch und Computer 2009*. Oldenbourg Publishing, Berlin, Germany 2009, 253-262.

18. S. Subramanian, D. Aliakseyeu, and A. Lucero, "Multilayer interaction for digital tables", *In Proc. of UIST '06*, ACM, New York, NY, USA, 2006, pp. 269-272.

19. B. Ullmer and H. Ishii, "The metaDESK: Models and prototypes for tangible user interfaces", *In Proc. of UIST '97,* ACM, New York, NY, USA, 1997, pp. 223-232.

20. J. Viega, M. Conway, G. Williams and R. Pausch, "3D magic lenses", In *Proceedings of UIST '96*, ACM, New York, NY, USA, 1996, pp. 51-58.

21. P. Wellner, "The DigitalDesk calculator: tangible manipulation on a desk top display", *In Proc. of UIST '91*, ACM, New York, NY, USA, 1991, pp. 27-33.

22. K.-P. Yee, "Peephole displays: pen interaction on spatially aware handheld computers", *In Proc. of CHI '03*, ACM, New York, USA, 2003, pp. 1-8.

23. ARToolKit. http://www.hitl.washington.edu/artoolkit