A COLLABORATIVE VISUALIZATION ENVIRONMENT FOR NATURAL INTERACTION WITH ARCHITECTURAL CONTENT

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ABSTRACT:

Interactive exploration and assessment of architectural design studies or reconstructions of historical built environments have for centuries been based on physical models from wood, plaster or cardboard. With the development of powerful 3D graphics functionality on personal computers, digital models of complex architecture (constructed or digitized) can be visualized and be explored interactively by means of advanced 3D computer displays. Virtual Reality based experiences can be used efficiently to provide detail views by means of virtual architectural walkthroughs as well as facilitate contextual views by adopting a birds-eye metaphor upon the data. One of the drawbacks of many 3D architectural presentations is that a correct 3D perspective is presented for a virtual camera with one predefined central perspective projection. In consequence only one if any of several observers benefits from a spatially correct view of the virtual scenery. In addition, for 3D presentations on vertical computer screens, natural interaction between two ore more collaborating users is hampered as direct face-to-face communication is distracted. In this paper we present results of our most recent development and ongoing work towards a more usable tabletop display system for two collaborating users and we present its application in the visualization of public buildings and historic environments. What renders our display environment specific is a combination of several features that make it feasible for everyday use: The technical design of our system allows for a compact form factor allowing the system to be used in everyday office situations. The system is capable of providing a dynamic stereoscopic 3D view for one moving observer, or alternatively monoscopic dynamic 3D views for two independently moving observers. This visualization environment is based on rear-projection and it incorporates an optical film into the screen which allows for high-resolution multi-point interaction at pixel accuracy using several optical digital pens that communicate wireless with the computer. In this paper we present the technical design of the system as well as its use in the visual assessment of building structures and presentation of pre-historical architecture. The main and most novel contributions of this paper are the results of an experimental study that investigated performance differences between natural pen-based direct interaction versus tradition mouse-based interaction in this new visualization environment.

1. INTRODUCTION

The use of a tabletop metaphor for computer displays has been appealing to various fields of applications, where people are used to work in a workbench or desk-side environment. The pioneering works by (Krüger, 1994) proposed this technology in medical training and simulation as well as in architecture. The use of similar display solutions have later been described for visualizations in automotive industry (Wesche, 1997) and in the field of implant surgery planning (Seipel, 1998). A fairly new area of application for tabletop display environments has been in command and control situations, where a number of decision makers gather around a shared scenario to discuss and collaborate on. In particular in the military field, the camp-fire metaphor has a long standing tradition and is well adopted in collaborative assessment and planning. This has recently led to a number of published evaluations of tabletop displays for command and control (Pettersson, 2005; Pettersson, 2004). What appears as an important requirement for these techniques to be really adopted by the users at daily work is, that they provide natural means of interaction between the users and between users and the system. Also, individualized presentations of content in a shared tabletop screen space requires comfortable solutions for head-position tracking as well as easy to use and robust techniques for image separation and multiplexing.

2. RELATED WORK

Some of the issues mentioned above have been addressed independently and differently throughout the past years, depending on the key requirements in the fields of application. Early published research was mainly targeting a single-user working situation or a scenario wherein a few collaborating users shared the same view from approximately the same viewing position (Krüger, 1994; Seipel, 1997; Fröhlich, 1995). The illusion of a 3D picture on the tabletop was thereby at first hand accomplished through dynamic observer-dependent projections, which was further supported by stereoscopic rendering. Stereoscopic pictures were accomplished by means of a time-multiplexing scheme and for accomplishing dynamic observer conditions the head position of one primary observer was tracked using state of the art tracking devices (magnetic, ultrasonic or camera based tracking). In the two-user responsive workbench (Agrawala, 1997) the temporal multiplexing scheme was extended further to utilize four separate time-slots enabling multiplexing two independent stereoscopic pictures onto the same physical display area. This method is both at the cost of decreased image lightness and suffers according to (Agrawala, 1997; Kitamura, 2001) from increased image flicker. In the paper describing IllusionHole a new approach was presented that allows individualized 3D graphics for more than three observers (Kitamura, 2001). In this display system the

horizontal screen is masked with a board at some defined distance. The board has compared to the effective display surface a relatively small aperture, through which observers in different viewing positions can see different sub-regions on the actual display. This sort of spatial partitioning of the available screen area into independent viewing zones is, however, at the cost of effective display size and resolution. In (Pettersson, 2005) a rear-projection tabletop display environment is described which provides four collaborating users with individual stereoscopic imagery. It employs eight independent projectors whereby pairs of two projectors have a unique projection angle upon the rear-projection screen. The screen incorporates a layer of custom tailored holographic grating to direct light from any two projectors towards either side of the quadratic tabletop display, respectively. Separation of stereo-image pairs is accomplished with linear light polarization. The general working principle behind this system is similar to the Lumisight Table which supports four independent users with individual, however, monoscopic imagery (Kakehi, 2005).
Technical solutions for stereo image separation under dynamic observer conditions seem until now, to be restricted to different types of light filtering (polarization and spectral filtering) or temporal multiplexing, which requires the use of some eye-wear. While little has been done to improve on this, meanwhile, many researchers have instead focused on developing intuitive and usable means of interaction for tabletop displays. Direct dexterous interaction with the display is being considered as one of the most intuitive and promising ways to design new forms of human-computer interaction. A technical solution towards this approach is the DiamondTouch system that allows multiple users to point and touch a screen. The system is based on electro-capacitive measuring techniques and is capable of detecting multiple points of interaction on a display. In the original paper, this system is presented in context of a tabletop display system based on front projection (Dietz, 2001).
Recently another inspiring presentation of what can be accomplished with multi-point touch interaction was given by Han et al. (Han, 2005). The novelty of their Multi-Touch Interaction Wall lies in the sensing technique which is based on internal infrared light reflection inside a glass screen and camera based tracking. This approach virtually allows for an arbitrary number of contact points to be detected.
Seamless integration of conventional paper and pen based interaction with digital content in table-based display environments was recently described by Haller et al. in their work on the Shared Design Space (Haller, 2005; Haller, 2006a). An interesting technical feature of their system is the tracking technology which comprises an optical pen device that can read a tiny dot pattern on printed media to identify its current location. Their work is based on front-projected imagery and the authors point out that rear-projected imagery interferes with the optical pen (Haller, 2006b).
Several earlier usability studies have evaluated different interaction forms, direct and indirect manipulation (Cohen, 1993;Forlines, 2006;Sears, 1991). In (Meyer, 1994) there is some evidence that indirect mouse input may equal or outperform direct "touch" input for tasks that require only one single point of contact. This was also the conclusion in (Forlines, 2007) when it comes to unimanual tasks on a large horizontal display. However, direct input tends to bee more convenient according to (Kobourov, 2005). Variations in the results and conclusions from these different studies suggest that interaction performance is strongly depending on the task to be solved.

3. DISPLAY REQUIREMENTS

Although recent advances in the design of interactive horizontal display devices have brought about solutions that convincingly demonstrate usability in real world applications, there still exist issues which today prevent these techniques to gain wider acceptance. Below is a list of issues we intended to tackle with our new tabletop system:

Front projection and occlusion: Many of the recent interactive approaches to tabletop touch displays are based on front projection displays since integrating the high resolution sensing technology into the screen interferes with light transmission through in a rear-projection configuration. In consequence, dexterous interaction causes shadows, which is a disturbing issue in multi-user working situations.

Form factor and complexity: Most systems presented so far do not offer a fully integrated compact solution. Ceiling-mounted on-top projection approaches require high clearance to ceiling as well as recalibration. Many of the integrated rear-projection solutions are very large owing to the throw lengths that are needed to accomplish the desired image size.
Other solutions as in described in (Pettersson, 2005) employ several projectors and require significant space for permanent installation.

Precision interaction: Despite the recent advances in touch sensing technology there is still need for improvements. For instance, unaided pointing and touching with bare fingers restricts pointing precision to some fraction of the size of a finger tip. Certainly, this positional accuracy is above the size of a pixel, which might be sufficient for many purposes. However, in e.g. geo-visualization and architectural applications, accuracy at least on the level of a pixel or less is necessary for precise point-based interaction.

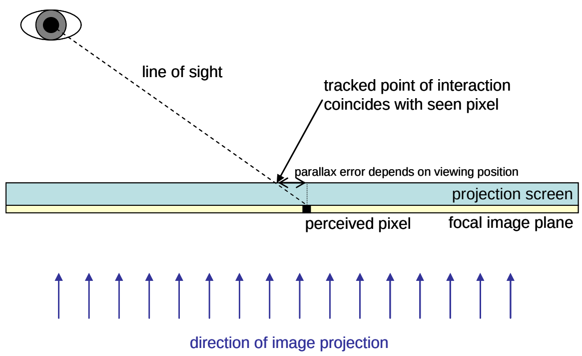

Figure 1. Occurrence of visual parallax.

Visual parallax error: Precise pointing or point-based interaction not only calls for high resolutions in positional tracking. It also requires that the sensed point of interaction coincides with the perceived position of a visualized structure which is at its extreme just a pixel. For many rear projection display systems the focal plane of the projected image appears on the rear side of the projection screen, which is usually considerably far away from the front side of interaction (see figure 1). This is particularly problematic for rigid rear-projection materials which require substantial thickness in a horizontal configuration to not suffer from bow. Furthermore, as is the case in some common rear-projection screens, the focal plane of the projection image is often not even clearly perceivable. Particularly when the screen material features rear-side Fresnel-lenses or front-side lenticular patterns for wide angle light diffusion, the perceived projection image often suffers from blur or diffusely localized focus.

Affordability: Finally, the prices for most commercially available systems including maintenance and operation are still prohibitive for occasional use of tabletop display environments.

4. INTERACTIVE DISPLAY SYSTEM

Our system configuration is composed of a number of commercially available components, which are genuinely combined to solve the above mentioned shortcomings. What makes the system finally work as desired is basically our choice of pen-based interaction and how we incorporated it into a rear projection configuration. A picture of the entire system showing all its components as described hereafter is shown in figure 2.

4.1 Computer system

The entire system is composed of and housed in a wooden cabinet of 86 cm height with an oval desktop surface with diameters d1=98 cm and d2=108 cm. The bottom of the cabinet has a rectangular footprint of 60 cm x 60 cm. Images are generated on a compact Pentium P4, 3.0 GHz computer system which is mounted at the bottom of the cabinet. It is equipped with a PCI-bus version of an nVidia Quadro FX1500 graphics card with 256 MB of on board video/texture memory. This graphics card is capable of stereoscopic, quad-buffered rendering for output of full-resolution stereo frames with frame sequential multiplexing at 120 Hz.

4.2 Primary display components

Computed imagery is displayed with a low-cost stereo-capable projector. We use an InFocus DepthQ 3D projector capable of displaying time multiplexed image sequences at 120 Hz at full resolution. The native resolution of this DLP based projector is 800x600 pixels and its light output is specified with maximum brightness of 1600 ANSI lumens. The digital projector is suspended on the upper side of the cabinet right underneath the table board. It is mounted in a sideways movable and pivotable fixation that allows for approximate image adjustments. The optical axis of the projector is pointing down towards the bottom of the cabinet.
At the bottom of the cabinet we mounted a first-surface mirror which reflects the projection image back upwards to the tabletop. This mirror is pressed into a special mounting frame by means of several rear-side coil springs. Fine-treaded adjustment screws on the front side of the mounting frame allow for fine angular adjustments of the mirror within its frame. The size of this mirror is 31 cm x 25 cm. The distance between the projector lens and the centre of the mirror surface is 48 cm. The distance from the centre of the mirror surface to the centre of the projection screen is 84 cm resulting in a total throw-length of 132 cm.

4.3 Head tracking

User interaction with a tabletop visualization system is two-fold. Besides interaction aimed at controlling the workflow of applications, for many visualization scenarios, dynamic observer conditions must be maintained. When 3D content is visualized, virtual objects must be correctly projected upon the tabletop display depending on the observer's instantaneous viewing position. To dynamically track users' eye positions, we mounted two TrackIR Pro cameras from NaturalPoint into the tabletop system. Each of the cameras covers its own range of interaction for two users collaborating from either of the "short" sides of the screen. The TrackIR cameras come with an on-chip logic that performs simple image segmentation of the raw infrared image data. It extracts bounding box-information for identified reflective targets and sends them though an USB connection to the host computer. Utilizing this low-bandwidth protocol, the cameras can maintain a tracking rate of approximately 80 Hz for multiple bounding boxes.
This raw bounding box information as delivered by the TrackIR cameras contains only data related to the 2D camera image. To determine 3D positions (i.e. depth) from that, we developed an own triangulation method, that evaluates the sizes and distances between bounding boxes of two retro-reflective markers mounted to either side of the stereoscopic eye-wear.

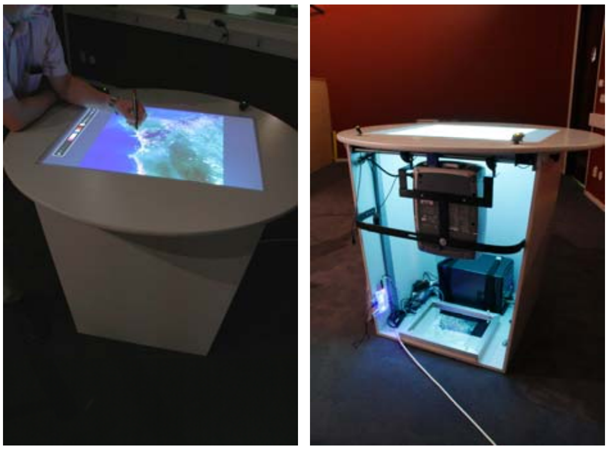

Figure 2. The integrated tabletop visualization system.

4.4 Image separation for collaboration

The use of one DepthQ 3D projector allows for a single user to perceive correctly projected stereoscopic imagery. While this is the standard way of using time multiplexed images in combination with alternatively switching shutter glasses, time sequential multiplexing can also be useful to individually partition information on screen for two users to increase efficiency in performance of a number of specific tasks (Pettersson, 2006). Our system exploits temporal multiplexing to generate two individually adapted views for two collaborating users. For this purpose we use low-cost wireless 3D glasses by eDimensional and manipulated their LCD shutters. We modified either of the two pairs of glasses so that shutters are opening and closing synchronously for the two eyes of any one user, however mutually exclusively for either one of the two observers. Hence, specifically adapted software can exploit the left- and right-buffers in stereo-rendering mode to display graphical content that is individually partitioned for either one of two collaborating users. When 3D content is supposed to be visualized for two users, a monoscopic yet perspective-corrected image is projected utilizing the 3D tracker data from one of the IRTrack cameras. In this mode of operation, 3D sensation is accomplished primarily through dynamic perspective cues and motion parallax (Arthur, 1993; Ware, 1993).

4.5 Pen based tracking

One of the design objectives is to support users with very high precision interaction that provides at least pixel accurate pointing in the displayed image. Inspired by the work of Haller et al. (Haller, 2006b) we decided for pen-based interaction since it provides, similarly to unaided pointing, a very natural means of interaction as well as opportunities for direct drawing and handwriting. We opted for an optical solution as patented by Anoto AB. Their digital pen was originally designed to digitize handwritten text on normal paper. It uses a patented dot pattern on a very fine grid that is printed with carbon ink on conventional paper forms. The Anoto pen used for writing on such paper features a built-in image sensor that recognises a neighbourhood of dots in the pattern. Only a small portion of the grid (6x6 dots) is needed to identify its unique distribution of points and to locate the pen's current position on the pattern. The high resolution dot pattern is to be printed with at least 600 dpi; the effective Anoto positional pattern resolution (dot pitch) is specified at 0,3 mm. Position offset errors are specified at a maximum of 0,7 mm; they vary with angle between pen and paper and the pen's location on the pattern. The Anoto digital pen accommodates a Bluetooth sender to transmit pen positions and stroke information to a nearby host computer. Anoto digital pens are built by different manufacturers and we used for our system as in (Haller, 2006b) the digital pen DP-201 manufactured by Maxell. Since we use the digital pen as an input device on screen only, we use an emptied ink cartridge in order to not scribble the display.

4.6 Projection screen

To integrate the pattern based optical tracking into a rear-projection configuration, we tried different materials to apply the specific Anoto pattern upon the front side of a rear-projection screen. Our final solution is based on a combination of a 5 mm thick glass as a bearing layer covered with two layers of semi-transparent architect film. The upper film is printed with an Anoto pattern in A0 format, whereas the lower serves as a light diffusing layer for the rear-projected images. We use the Océ transparent polyester film LFM 310. The A0 pattern is cut to the same size as the glass, which is 69 cm by 52 cm. The glass layer resides on a 6 mm deep and 8 mm wide reset along the edges of the rectangular cut-out in the tabletop (see figure 2, left). The top of the glass surface is therefore 1 mm below the surrounding surface of the tabletop. No glue or adhesives are used to fixate the semi-transparent Anoto pattern in place. Instead, when we cut to same size as the glass, the architect paper is kept in place due to the 1 mm reset surrounding the glass and, seemingly, due to electrostatic adhesion (LFM 310 is not antistatic material). The glass we used is treated with an anti-reflective coating to avoid back-reflections of the rear-projected image to the mirror which would cause double images on the screen.

5. INTERACTION STUDY

The tabletop display environment described in the previous section offers new opportunities to directly interact with the visualized content at pixel precision, rather than using indirect interaction with subtle mouse movements. However, basic physics states that the greater the length and mass of an object, the greater its inertia is and the greater is the force required to move it. This suggests variations in the interaction performance depending on if the mapping of the user input is direct, as in the case with a digital pen, or relative as in the case using a mouse.

In order to investigate potential benefits or tradeoffs of direct, pen-based interaction, we conducted an experimental study to investigate differences between direct pen-based interaction and indirect interaction using a mouse. To that end we designed an interaction task to be solved by test persons under three different conditions:

- Vertical display with mouse interaction
- Tabletop display with mouse interaction
- Tabletop display with pen based direct interaction.

5.1 Experimental task and stimulus data

The general task to be solved by subjects involved a sequence of precise picking of graphical targets. The visual stimulus consisted of a collection of 12 red coloured filled circles and 20 green coloured filled squares spread out randomly in adjacent and partly overlapping areas on the screen. The footprint size of the targets was 3,9 mm^2 on screen for both the circles and the squares. To solve a trial, subjects had to clean up the display from all red targets. Removing a red target required first selecting a red target followed next by the selection of a green target.

Selection of targets involved positioning of the cursor and left clicking with the mouse, or tapping once with the digital pen, respectively. Successful selection was visually prompted by changing the colour of the chosen target to yellow.

The selection of a green target would make the green square target as well as the previously selected circle target (now yellow) disappear from the display. A green target could only be selected after prior selection of a red target. The trial was solved, when all red targets had been removed from the screen. The entire task involved 8 trials per individual with randomly different stimulus pictures (figure 3).

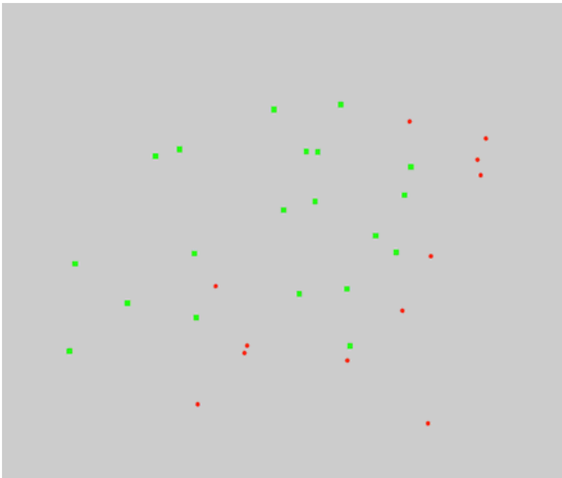

Figure 3. A stimulus from the experiment

5.2 Experimental apparatus and procedure

The Tabletop apparatus described in section 4 was used for the experimental setup. The actual size of the projected image was 62cm x 47cm with a resolution of 800 x 600 pixels, resulting in a pixel size of 0,75 mm^2. To maintain the same display condition for the *Wall display* we used a rear projection onto a display area of the same size as the tabletop display and using the same optical film with imprinted pattern just as on table display. For indirect interaction an ordinary mouse device was used and for direct interaction the Anoto pen described in section 4.

Instructions were given to perform the trials as fast as possible but at own pace and a test trial was run before each of the interaction methods started. The test began with a blank blue screen; then subjects started the experiment by clicking or tapping once somewhere on the screen, to activate a sequence of 8 randomly different trials to solve. At the end of each trial, when all red targets had been cleaned up, the display went blank again and the next trial in the sequence was started on the user's own pace by tapping or clicking at some arbitrary position.
All subjects made three tests, one with each interaction form. The design was counterbalanced between subjects through permutation of the test configuration; the first subject started with wall and mouse interaction, the second with table and mouse interaction, third with table and pen interaction etc. Between the tests there was a short brake. The independent variable in the experiment is the type of interaction. Dependent variables observed are times and distances between any two red and green targets. Subjects were also asked to verbalize their preference in regard to the interaction form with a motivation. The time needed by subjects to solve the 8 trials in all conditions was about 30 minutes.

5.3 Subjects

We chose to test a narrowly defined user group consisting of 12 undergraduate students at the University of Gävle, 7 men and 5 women for the test. All were right handed, with good computer experience and aged between 18 and 35 and with good or corrected to good sight. The participants were paid in form of a lunch coupon to the campus restaurant.

5.4 Basic statistics

An initial test revealed that the collected data was not totally normal distributed; therefore a more conservative non-parametric Man-Whitney test was used for statistical analysis. The significant level set to 0,05 in all tests. 8 stimuli x 12 target x 12 participants resulted in 1152 distance and time observations for each interaction method. Microsoft Excel and the plug-in Analyse-it were used for statistical analysis and to generate the diagrams and tables.

5.5 Results

One strategy adopted by subjects was to choose circles and squares with the shortest need for movement in the beginning of the trial, and subsequently the distances tendet to increase (see figure 4). This strategy was apparent in all three interaction methods, however, mean distances for selected targets was at p<0,0001 significantly longer for the Wall/mouse interaction, compared to Table/mouse. No difference between Table/mouse and Table/pen interaction could be observed. Analyzing mean time per target reveals that the Wall/mouse condition clearly outperformed the Table/mouse interface (p<0,0001) and that the Table/pen condition outperformed both other forms of interaction , each at p<0,0001 (figure 5). In terms of speed measured in average time in ms per pixel, there is an evident pattern for all conditions that clearly indicates decreasing travel times per pixel for increasing target orders within trials. Obviously shorter travel times per pixel coincide with larger travel distances from the distance observations. In other words, average speed for the motion between targets-pairs increases with the distance between those pairs. This characteristic pattern in the decrease of average times is similar for all conditions, however, absolute levels are significantly higher (i.e. slower speeds) for the Table/mouse condition at p<0,0001 (figure 6). No significant differences depending on the order of tested interaction forms were discovered.

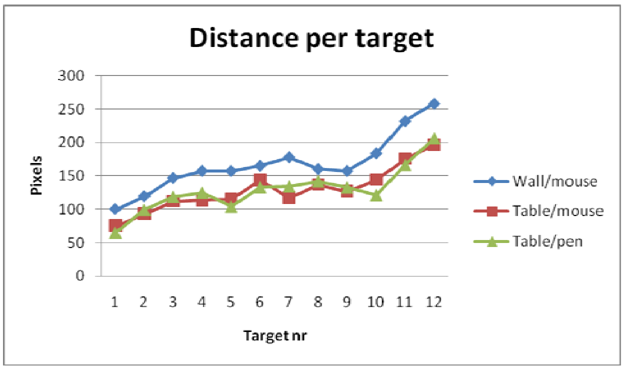

Figure 4. Distance per selected target

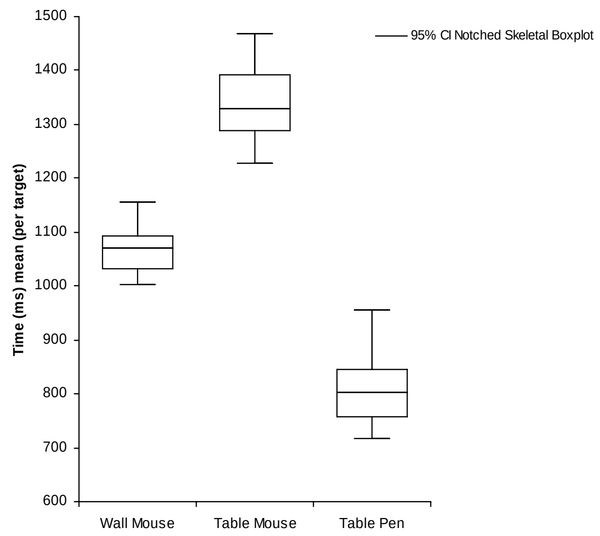

Figure 5. Time per target.

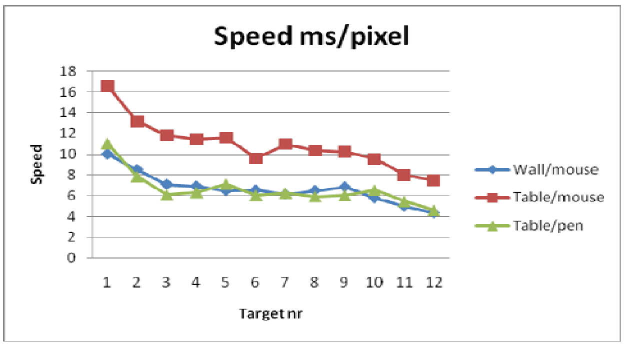

Figure 6. Speed per target

The users' verbalized opinions were congruent with the observed data; 11 out of 12 subjects preferred Table/pen interaction with Wall/mouse as their second choice. Only one subject preferred the Wall/mouse as it is most similar to an ordinary interaction situation. This subject ranked the Table/pen as second best. None of the subjects appreciated the Table/mouse interaction form.

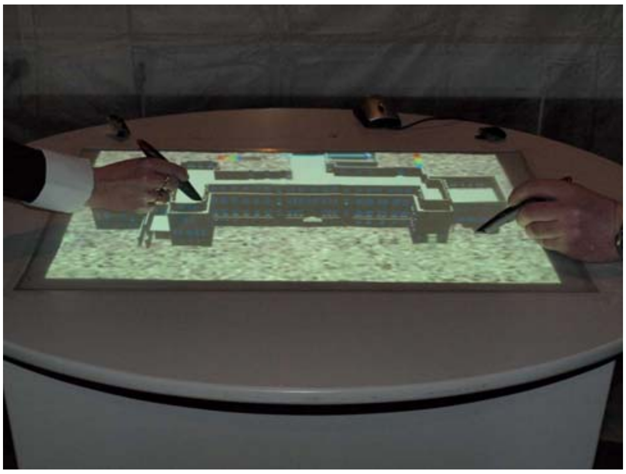

Figure 7. Collaborative visualization of maintenance intervals for a large building complex.

Figure 9. Interactive visualization of a stone-age village.

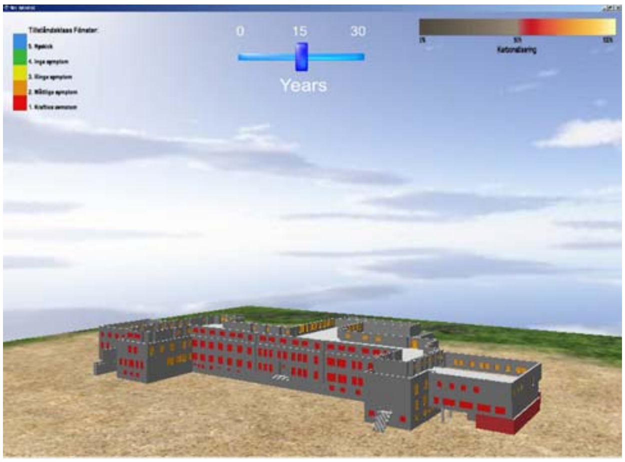

Figure 8. The architectural visualization in a common, first person perspective.

Figure 10. First person perspective of the interactive stone-age village.

6. ARCHITECTURAL APPLICATION

The integrated tabletop display presented in section 4 is a very suitable environment for collaborative exploration of architecture as it provides the means for cooperative interaction as well as it facilitates an unhindered face-to-face dialogue for several users. In our ongoing work we demonstrate the system in two showcases in the field of architecture and historic built environments.

The architectural application is aimed at supporting housing companies in building life-cycle management i.e. the analysis of the aging processes of building materials and buildings maintenance. In the current case, we visualize building structures of a hospital as a natural 3D model. This natural model provides the spatial context to visually present when in a timer-perspective maintenance is expected to be needed in different parts of the building complex. In our data model the representation of the geometric 3D model of the building structures is augmented with a building material index. Based on an empirical model of material weathering/aging for various materials and using local data in regard to weather exposure, air quality and other environmental factors, the demonstrator application estimates expected time intervals for future maintenance procedures.

The temporal domain can be explored using a slider bar on a time scale. Time intervals are visually coded with distinctive colours. Building structures which are expected to be in need of maintenance for the currently chosen time interval are augmented with the corresponding colour in the 3D building model. Figure 7 shows the application at use in our tabletop visualization environment. For the purpose of a correct illustration in figure 7 and 9, the camera lens was equipped with the head position tracking device; hence the perspective view rendered on screen is what would be seen by a head tracked observer positioned at the cameras location.

To better illustrate the contents of what is visualized in this demonstrator application, figure 8 presents a screen capture of the same application when run in a normal screen mode using a first person perspective. As can bee seen in this situation, the windows facing towards the observer are those parts of the building that are in most urgent need of maintenance.

The second application scenario (shown in figures 9 and 10) is a visualization of a stone-age village and its simple architecture from the period between 3400 and 3000 bc. The reconstruction and visualization is based on the findings from excavations at Valbo, Sweden. It comprises the archaeology of huts and fortifications in the ground, as well as the remains of fireplaces, tools and weapons. The site has been recreated using elevation data from a GIS database to reconstruct the former strandline which as a consequence of the raising of the landmass today is located many kilometres from the actual site.

The interactive visualization at the tabletop using a pen-based interaction device is aimed at supporting museum visitors to interact in a natural manner with the historic content. Both demonstrator applications were developed using the high-level 3D software development toolkit Vizard 3.0 from WorldViz.

7. DISCUSSION AND CONCLUSION

7.1 Results from the experiment

A finding from our experiment is that users generally prefer a strategy that minimizes cursor travel distances as far as possible. This observation holds generally for all three test conditions. However, in the vertical display configuration, when using a mouse as interaction device, distances were always larger for all trials during the experiment. In comparison, for the tabletop visualization, those distances were evidently shorter and there was no apparent difference in the distances when using a mouse as input device or when using direct input with the pen, respectively. This observation suggests that the selection of visual targets to be picked is more governed by the visual assessment rather than input modality i.e. it is depending more on the display mode (horizontal versus vertical) rather than on the input modality (indirect or direct). When finding shortest distances among a number of possible targets as in our task, a birds-eye overview upon the screen apparently improves finding the shortest distances.

Another interesting finding related to these results is the fact that for increasing cursor movements needed to select the targets, travel times did not differ between relative mouse-input on a vertical screen and absolute pen-based input at a table. This finding is contra-intuitive, as larger target distances on the horizontal tabletop screen require significantly more hand and arm motion for pen-based input when compared with mouse based, relative input.

Relative mouse input was significantly less efficient when used in the tabletop setting as compared to the vertical display setting. This observation might be explained with the fact that users from daily routine are generally better trained to handle horizontal mouse-movements with visual feedback of cursor movements on a vertical screen rather than the other way around. But the influence of other factors may not be ruled out, such as different ergonomic conditions when users interact at the tabletop in a standing posture, or more restricted space for mouse movement at to the table top display.

Finally, we conclude that the tabletop presentation with direct pen-based input outperformed all other conditions i.e. it is significantly more efficient for picking and selection of visual targets than relative mouse-input on conventional vertical screens. Direct pen-based input provides a natural form of interaction which is even for large distance cursor movements at least as fast as conventional mouse interaction, if not better.

7.2 Experiences from practical use-cases

The positive observations from the interaction experiment are also confirmed by the users' subjective findings that the pen-based input in the tabletop environment provided the most convenient means of interaction. This affirms us in our ambition to further promote tabletop visualization environments with direct input for applications where several users work collaboratively or in cases where untrained users on a sporadic base interact with graphical content as for instance in museums or other public settings.

The architectural application for life-cycle management of materials in complex buildings has in a preliminary informal evaluation with a few experts demonstrated large potential benefits compared to the traditional methods of evaluating and assessing maintenance intervals. The use of a tabletop visualization environment for collaborative exploration is novel in this field of application and opens up for new opportunities to support the professional dialogue between housing and real estate companies and their customers.

The application in the field of cultural heritage and archeology has not yet reached a state of development where it could be deployed to end users; therefore evaluations are yet to be performed.

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