Cubby: A Unified Interaction Space for Precision Manipulation

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ABSTRACT

Precision manipulation in VR poses special requirements. One such requirement is the unification of the display and manipulation spaces, i.e. that the user manipulates a virtual object at the place where it appears. We describe the problems associated with unification and give an overview of VR systems which aim to realize or actually realize unification. To address the problems associated with unification we developed a desktop VR system named Cubby. We compare Cubby to existing unified systems and argue its superiority for precision manipulation.

INTRODUCTION

There is a need for virtual reality (VR) systems which support precision manipulation tasks. One example is surgical simulation. In his natural environment, a surgeon is confronted with tasks that require high precision. Lack of precision may have severe consequences. He therefore needs very fine control over his instruments. With a scalpel the surgeon may round a corner whilst simultaneously changing the angle and depth of the cut. During the procedure he approaches the operative field from different angles, both visually and instrumentally. Another example of a precision task is modelmaking such as found in industrial design, architecture and various engineering disciplines. A modelmaker exercises fine control over his tools to sculpt and cut his materials. To better judge his model and to find a convenient angle for his tools he frequently changes his view on the model.

It is hard to support such precision manipulation tasks in a VR system. Systems based on helmet mounted displays (HMDs) typically lack the resolution and tracking accuracy required for precision manipulation. And with the current devices for head and hand tracking, it is not possible to realize high accuracy within a large space, such as a CAVE [2]. With the currently available technology, head-tracked desktop displays offer a smaller, but more stable workspace.

To create a VR system optimized for precision manipulation, we have taken natural skills in precision tasks as our starting point. In the natural environment, people manipulate objects where they appear, unlike the typical computer setup where we see virtual objects on a screen but act on these objects through a pointing device held at another position. We call a VR system in which we can manipulate virtual objects where they appear a unified system, since it unifies the display and manipulation spaces. Unification is worth pursuing since experimental literature shows that disruptions of hand-eye coordination have a negative impact on manipulation performance. For example, in an endoscopy task, performance decreased considerably when the angle between the display and manipulation space exceeded 45˚ [18]. Everyday tasks are also impeded when visual feedback is transformed (See, e.g., [8] for a discussion and overview). As we will explain, a unified system poses its own problems and challenges though.

We start with the requirements for unified systems, the perceptual conflicts which these requirements lead to and refer to the

Figure 1 Cubby is a unified VR system: the user manipulates virtual objects at the place where they appear.

literature on various unified VR systems. We then present a VR system named Cubby (Figure 1) which was designed with precision manipulation and unification in mind. We discuss the decisions made in the design of Cubby and argue why Cubby is well-suited to precision manipulation.

UNIFICATION

Requirements

A unified VR system for precision manipulation, i.e., one in which the tools cut where we hold them, must satisfy at least the following two requirements:

Accessibility—It must be possible for the user to enter his hand or an instrument, into the virtual scene.

Head-tracking support—When the user moves his head, his view of the virtual scene must change in the same way as his view onto his hands. This means that the graphics are generated through head-tracked perspective. Without head-tracking support, it is not possible to maintain the illusion that the user acts at a particular spot on a virtual object, when the user moves his head.

Perceptual conflicts

The requirements accessibility and head-tracking each lead to a perceptual conflict which seriously impairs the usability of a VR system.

Occlusion conflicts—Occlusion occurs when the user tries to reach behind virtual objects floating in front of the screen (Figure 2). The virtual objects cannot occlude the hand or instrument, even when they appear closer to the observer. The resulting conflict between occlusion and perceived depth is disturbing [20].

Clipping—Clipping involves the cutting off of virtual objects by the monitor's edges [9]. This is particularly problematic with single screen, head-tracked displays. Such displays can make the virtual scene float in front of the monitor screen (Figure 2) but only within the viewing pyramid whose base is the screen and whose apex is the eye of the user. As the user moves his head, parts of the scene that lie outside of the pyramid get 'cut off' optically by the edges of the display behind them. As a result the 3D impression collapses. To avoid clipping, the virtual scene in a single-screen display, such as shown in Figure 2, cannot protrude far in front of the display. Together with the accessibility requirement, which

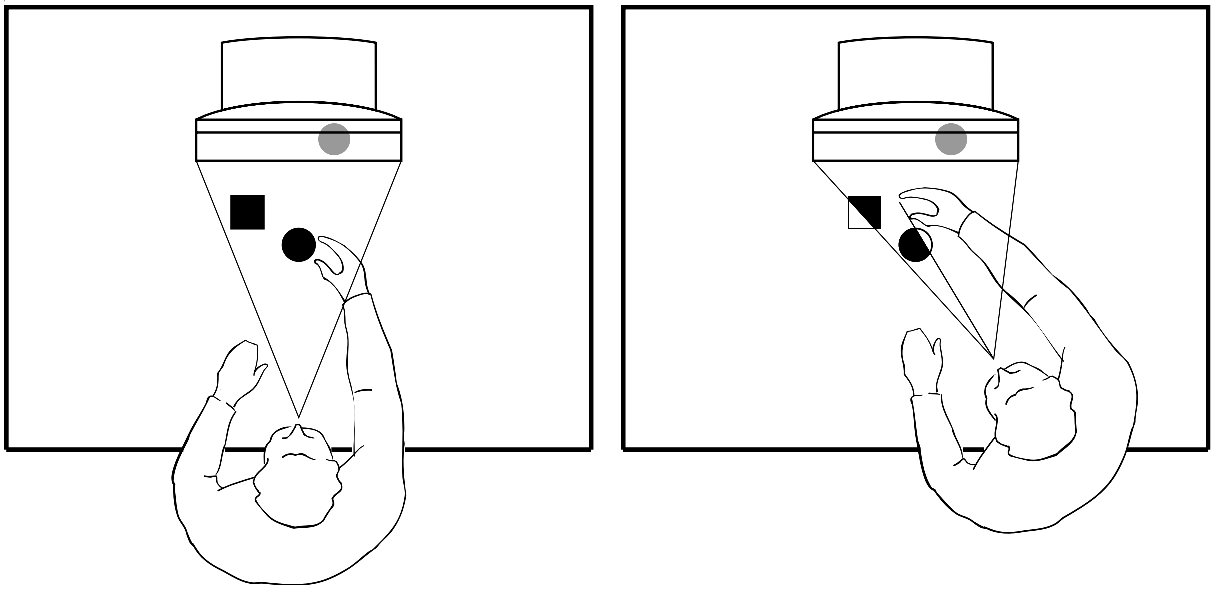

Figure 2 Problems with unified systems. The grey virtual sphere behind the screen is inaccessible to the user. When the user moves his hand behind the black virtual sphere, this object cannot occlude the hand. When the user moves sideways from the neutral position, the cube is clipped by the left edge of the display.

states that the virtual scene may not lie behind the screen, the available unified workspace of a single-screen setup is very small compared to its display size.

Unification in existing systems

Over the years there have been a number of systems which aimed to realize or actually realized unification. First, we describe them, then we compare them.

In a system by Schmandt [17], one of the pioneers of unified systems, the user sees the stereoscopic image of a CRT placed at a 45° angle reflected in a half-silvered mirror parallel to the floor. The user can reach underneath the mirror into the 3D scene and paint in 3D or input vertices with a six degrees of freedom instrument. Schmandt's system does not make use of head-tracking. The assumption is that the user will not move his head and that the user's point of view, which is measured at the beginning of a session, will stay valid during a session.

Kameyama et al. [14] solve the accessibility issue by using two concave mirrors to translate the image of an autostereoscopic volume scanning LCD panel into another free space. The virtual objects can be manipulated with a wireless three degrees of freedom pen. Because of the volume scanning display, stereoscopy and head-tracked perspective are inherent to this system. Kameyama et al. [13] also describe a similar set-up but with the optical relay system replaced by a half-silvered mirror.

Ishii et al. [12] developed a unified system with a stereoscopic, head-tracked, single screen display and a mechanical six DOF pointing device with force feedback. To solve the occlusion problem they use a virtual pointer which is rendered as an extension of the physical pointing device.

The Reachin desktop displays [16] are similar to the Schmandt setup with the difference of offering force-feedback. They use a stereoscopic display with a six degrees of freedom mouse mounted on a force-feedback arm. As with the Schmandt setup, the Reachin displays do not offer head-tracking. The developers of Reachin use the term co-location for unification.

Finally, there are two unified systems which both use head-tracked stereoscopy on a screen the size of a drafting table. These are the Responsive Workbench [15] and the ImmersaDesk [3]. The main difference between the two systems is that while the Workbench has a horizontal screen, the screen of the ImmersaDesk is placed under 45°. Accordingly, the Workbench is better suited to tasks which in the real world are performed on a table, while with the ImmersaDesk it is easier to view both the front and the top of a virtual model without clipping occurring.

Table 1 shows how each system exhibits one or more of the problems of unified systems or exhibits one or more of the perceptual problems. Note that the Workbench and ImmersaDesk try to solve the clipping

Table 1 Systems compared on unification requirements and perceptual conflicts

	accuracy	requirements fulfilled?		perceptual conflicts solved?	
		accessibility	head mov. support	occlusion	clipping
Schmandt [17]	no (CRT induced jitter)	yes	no (could be added)	no (transparent)	no
Kameyama et al. [15]	no (display resolution)	yes	yes	no (transparent)	no
Ishii et al. [12]	yes	yes	yes	yes (virtual tip)	no
ReachIn [16]	yes	yes	no (could be added)	no	no
Workbench [15]	yes	yes	yes	no	partially
ImmersaDesk [3]	yes	yes	yes	no	partially
CAVE [2]	no	yes	yes	no	yes
Cubby [1][4][5]	**yes**	**yes**	**yes**	**yes (virtual tip)**	**yes**

problem by using displays which are large compared to the virtual scene. This is only a partial solution though as low viewpoints (Workbench) and side views (ImmersaDesk) are still not possible to obtain.

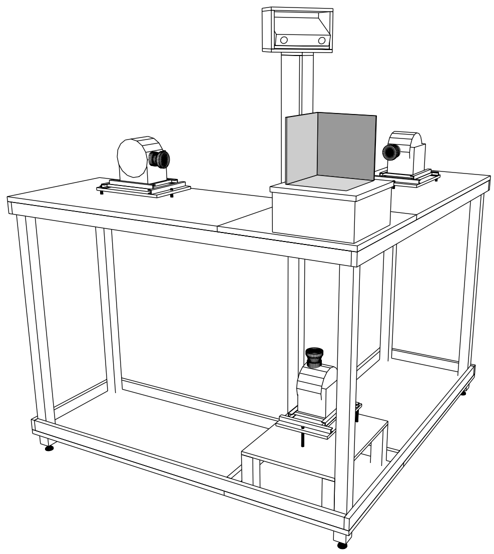

Figure 3 Configuration of Cubby.

CUBBY

In this section we present a virtual reality system entitled Cubby [1][4][5], developed with precision manipulation and unification in mind. Cubby uses three orthogonal head-tracked displays which form a cubic space (Figure 3). Through the coupling of the perspectives on all three screens to the head-movements of the observer, the illusion is created that virtual objects stand inside the cubic space (Figure 4). Technically, this is similar to CAVE, only much smaller, and the user's head is outside the cube (We will return to the advantages of these differences below). Manipulation in Cubby is done by means of an instrument which behaves as a pair of tweezers. Figure 1 shows a user manipulating virtual objects in Cubby. Head-position measurement is done by an infra-red system (Origin Instruments Dynasight). Measurement of the instrument's position and orientation are done through an electro-magnetic position and orientation tracker (Ascension Flock of Birds). More detailed information on Cubby can be found at www.io.tudelft.nl/id-studiolab/cubby/index.html. A detailed software description of the visualization part of Cubby can be found in [6][7] and [10].

On Cubby and unification

Cubby satisfies the requirements for unification of the display and manipulation spaces. First, the virtual objects are directly accessible to an instrument, since they appear inside the cubic space and in front of the screens. Second, all three screens respond to changes in head-position. Third, because head and instrument tracking are separated and cover a small space, high accuracy can be realized.

On Cubby and perceptual conflicts

In Cubby the perceptual conflicts associated with unified systems have been eliminated or at least alleviated.

1. Occlusion conflicts

To reduce the occlusion problem, Cubby uses a hybrid instrument with a physical

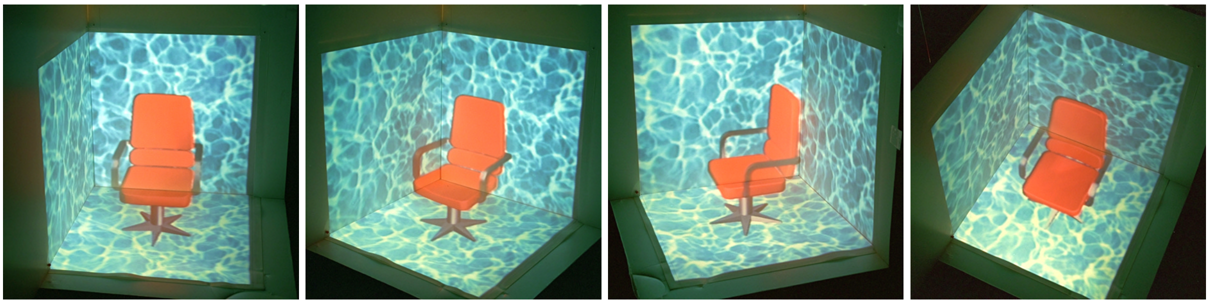

Figure 4 A virtual desk chair seen from different points of view, generated by various head-positions.

barrel and a virtual tip. This approach is similar to that of [12] mentioned earlier, with the difference that with Cubby the instrument is not mounted on a mechanical, force-feedback arm. The tip is rendered as an extension of the physical barrel (Figure 5). The virtual pointer is rendered with the scene and can be moved behind a virtual object without occlusion anomalies occurring. Because Cubby allows viewing from many angles the user can choose a viewpoint from where objects in the virtual scene are not in conflict with the physical part of the pointer.

2. Clipping

Cubby's display layout greatly reduces the clipping problem. Figure 6 shows how, when a virtual object is clipped by the inner edge of one screen, the clipped part appears on the adjacent screen. As a result, the user can view the scene from many sides, and virtual objects can be placed in a larger workspace.

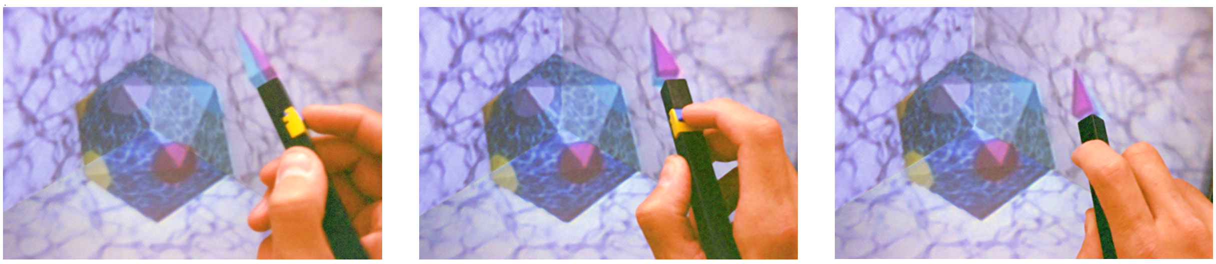

Figure 5 The virtual tip forms an extension of the physical barrel.

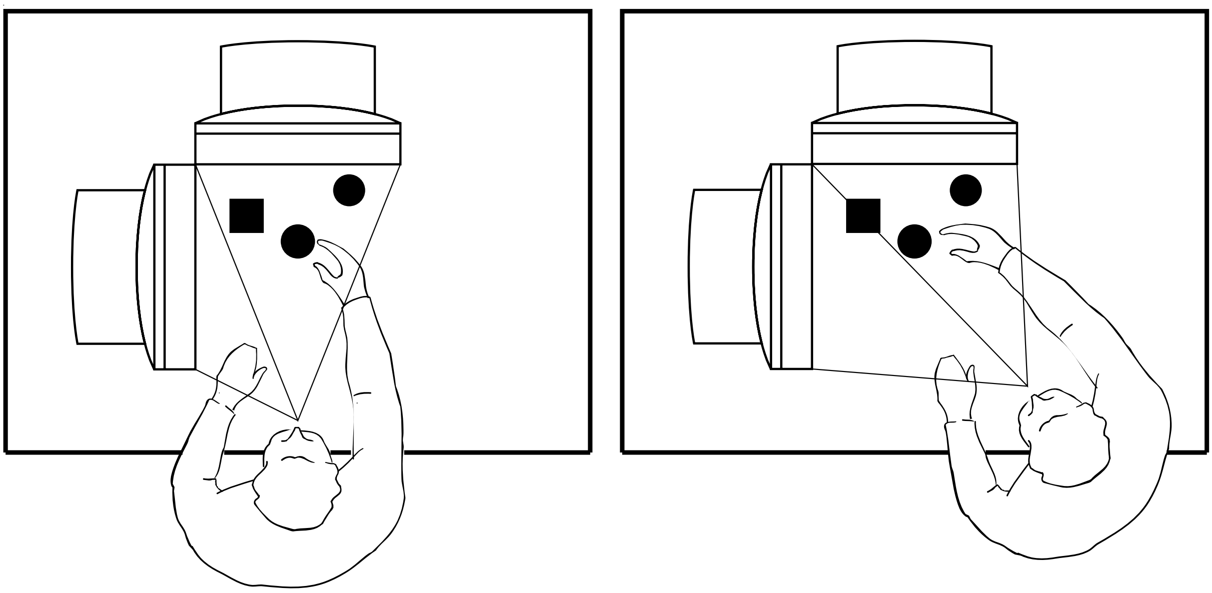

Figure 6 When the user moves sideways from the neutral position, the black cube is clipped by the left edge of the first display but continues on the second display.

On Cubby and precision manipulation tasks

We list the design decisions which are important to support precision manipulation.

1. Non-encumbering

If the user is to perform with high accuracy, a VR system should influence his movements as little as possible. In Cubby, the head-sensor is a small reflective disc (ø7mm) which can be applied to existing glasses or a minimal spectacle frame. While the instrument is not wireless, it minimally hinders the user's movements and is easy to pick up and put down. These choices for head and instrument tracking make it easy for the user to detach from the system, which is important if the system is to be integrated in the work flow [11].

2. Accurate depth perception from a wide range of angles

With Cubby the user can view a small and complex virtual scene from a wide range of angles without clipping. For the current Cubby prototype we decided to use head-tracking, but no stereo. Head-tracking by itself offers a convincing depth impression [19], as one can experience by walking around and manipulating in the real world with one eye closed. Not using stereo has two advantages. From a user-friendliness point of view, this setup requires very little headware as shutter or anaglyph glasses are not needed. From a technical point of view, using only head-tracking requires half the calibration and rendering power. That being said, accuracy of depth perception could be further improved by adding stereoscopy in a trade off with headware.

3. Accurate manipulation

Because the electro-magnetic instrument tracker is not used to track head-position, it can be dedicated to cover only the much smaller workspace. The cubic manipulation space is compact. This is advantageous, since electro-magnetic tracking systems are more accurate at a small range. The open cubic space allows the user to enter the instrument into the virtual scene from a wide range of angles. Accuracy of the electro-magnetic tracking is further enhanced by using screen projection, so no electronic

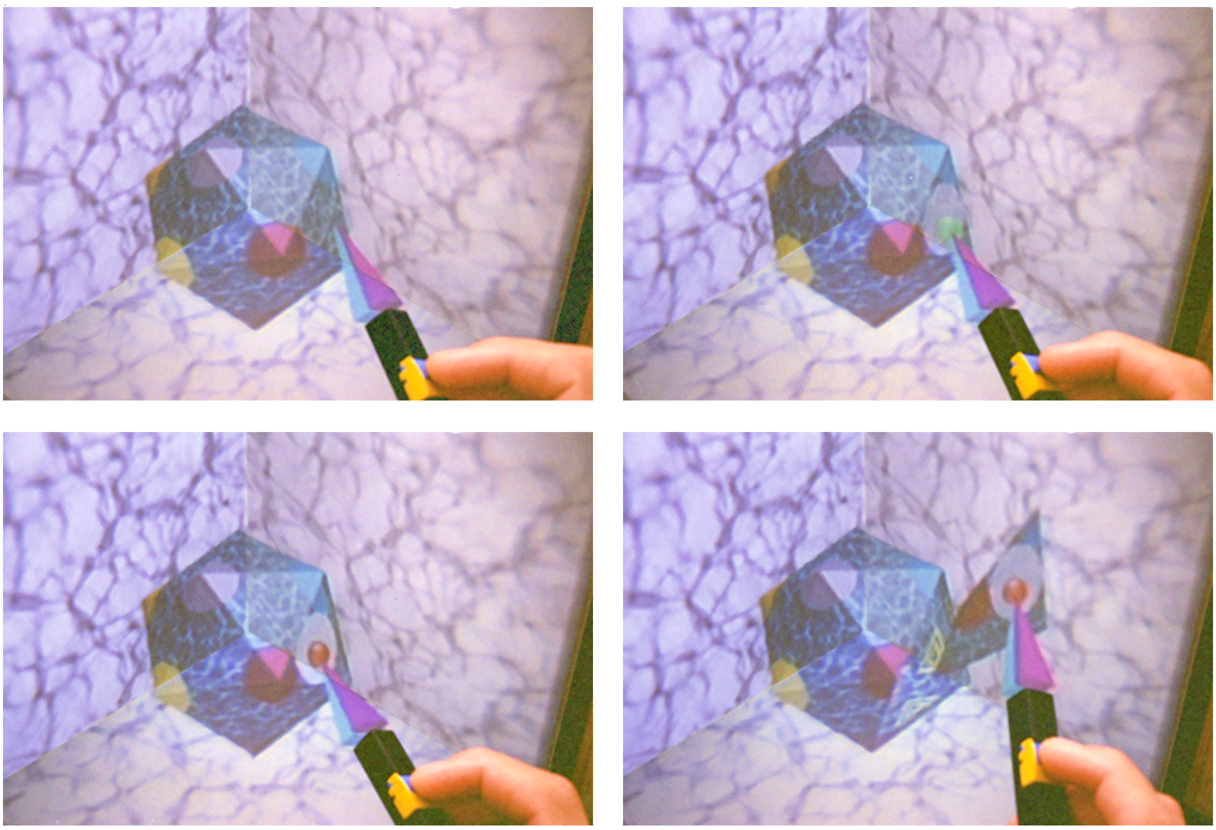

Figure 7 Feedback: The instrument approaches the polygon (top left). As the virtual tip enters the sensitive zone of a polygon the inscribed circle lights up, a small green sphere appears at the point of contact and a collision sound is heard (top right).The closer the tip gets to the polygon, the brighter the inscribed circle and the more saturated the colour of the sphere. After the user presses the button on the instrument, the sphere turns from green to red (bottom left), and the puzzle piece follows the instrument in both orientation and position. Pressing and releasing the button also results in auditive feedback.

components are near to the tracked cubic workspace.

The interaction style that we implemented between the hybrid instrument and the virtual scene is shown in Figure 7. The mechanism of visual and auditive feedback described in the subscript of Figure 7 is meant to compensate for the lack of haptic feedback. The feedback is a sign to the user that object can be manipulated.

CUBBY AND CAVE

As mentioned above, Cubby is technically similar to CAVE. However, from an application point of view we think Cubby is different in ways which make Cubby better suited to precision manipulation. First, because the display space is small compared to that of CAVE, instrument tracking is more accurate. Second, Cubby and CAVE invite different behaviour. CAVE offers a panoramic view and thus the observer is invited to look around him, rotating about his axis, rather than look around an object. Cubby offers a much smaller scene and therefore the user will look around it. Cubby is thus targeted specifically at precision manipulation rather than at panoramic viewing or walk-throughs. Third, because of its smaller size Cubby is less expensive than CAVE. Not only does the smaller size decrease the cost of physical components such as projection screens, it also decreases the cost of the required computer hardware. Fourth, Cubby takes up little space. Its footprint could be made even smaller by simple means, such as the folding of projectors' light paths. Because of its small size and because it is self-contained, Cubby is not fixed to one particular room, but can be moved to a space where it is needed.

CONCLUSIONS

Precision manipulation in VR poses special requirements not met by current VR systems. We designed Cubby to address these problems. Unification of the display and manipulation spaces formed an important part of our approach. Our current Cubby prototype shows that it is possible to offer unification whilst avoiding occlusion and clipping problems. For our future research we have set two goals. The first is to implement two-handed interaction in Cubby. The second is to reduce Cubby's footprint and make it desktop-sized using state-of-the-art display technology.

ABOUT THE AUTHORS

Tom Djajadiningrat (1968) holds a BSc(Hons) in Industrial Design from Brunel University of Technology and an MDes in Industrial Design Engineering from the Royal College of Art. After obtaining his PhD on Cubby [5] at the department of Industrial Design of Delft University of Technology he stayed on as an assistant professor. His research focus is interaction design for electronic products and computers with an emphasis on tangibility and expressiveness.

Kees Overbeeke (1952) studied psychology at the Leuven Catholic University (Belgium). He specialised in perception and mathematical psychology. In 1988 he completed his PhD 'Depth through movement' at Delft University of Technology. Now an associate professor, his research and teaching interests include design & emotion, expressivity and experience of products, and the resulting new philosophy of science and methodology.

Pieter Jan Stappers (1959) was originally trained as a physicist, and joined the research group at the department of aesthetics in 1984. Research topics focused on perception theory, spatial representation, spatial thinking and imagery. Since 1997 he is associate professor of design techniques, research efforts focusing on design tools for the support of ideation skills.

REFERENCES

[1] Buxton, W. & Fitzmaurice, G.W. (1998). HMDs, Caves & Chameleon: A human centric analysis of interaction in virtual space. Computer Graphics, The SIGGRAPH Quarterly, 32(4), 64-68.

[2] Cruz-Neira, C., Sandin, D.J., & DeFanti, T.A. (1993). Surround-screen projection based virtual reality: The design and implementation of the CAVE. *Proceedings of SIGGRAPH'93*, 135-142.

[3] Czernuszenko, J., Pape, D., Sandin, D.J., DeFanti, T.A., Dawe, G.L., & Brown, M. (1997, May). The ImmersaDesk and Infinity Wall projection-based virtual reality displays. *Computer Graphics*, 31 (2), 46-49.

[4] Djajadiningrat, J.P., Smets, G.J.F., & Overbeeke, C.J. (1997). Cubby: a multiscreen movement parallax display for direct manual manipulation. *Displays*, 17, 191-197.

[5] Djajadiningrat, J.P. (1998). *Cubby: What you see is where you act. Interlacing the display and manipulation spaces*. Doctoral dissertation. Delft University of Technology, Delft, The Netherlands.

[6] Djajadiningrat, J.P. & Gribnau, M.W. (2000). Cubby: Multiscreen Desktop VR Part I. Multiple views and mirroring images in QuickDraw 3D. *MacTech* 16(9), 80-96.

[7] Djajadiningrat, J.P. & Gribnau, M.W. (2000). Cubby: Multiscreen Desktop VR Part III. Reading an input sprocket device and calibrating Cubby. *MacTech* 16(12).

[8] Dolezal, H. (1982). *Living in a world transformed. Perceptual and performatory adaptation to visual distortion*. NY: Academic Press.

[9] Fisher, S. (1992). Viewpoint dependent imaging: An interactive stereoscopic display. *SPIE Processing and Display of Three-Dimensional Data*, 367, 41-45.

[10] Gribnau, M.W. & Djajadiningrat, J.P. (2000). Cubby: Multiscreen Desktop VR Part II. How to create an Input Sprocket driver for a 3D input device. *MacTech* 16(11).

[11] Hinckley, K., Pausch, R., Goble, J.C., & Kassell, N. (1994). Passive real-world interface props for neurosurgical visualization. *Proceedings of CHI'94*, 45-458.

[12] Ishii, I., Karasawa, T., & Makino, H. (1994). A method of handling virtual objects that incorporates the sense of touch. *Systems and Computers in Japan*, 25 (10), 72-81.

[13] Kameyama, K., & Ohtomi, K. (1993). A shape modelling system with a volume scanning display and multisensory input device. *Presence*, 2 (2), 104-111.

[14] Kameyama, K., Ohtomi, K., & Fukui, Y. (1993). Interactive volume scanning 3-D display with an optical relay system and multidimensional scaling. *SPIE Stereoscopic Displays and Applications IV*, 1915, 12-20

[15] Krüger, W., & Fröhlich, B. (1994, May). The Responsive Workbench. *Computer Graphics and Applications*, 14 (3), 12-15.

[16] Reachin: http://www.reachin.se

[17] Schmandt, C.M. (1983). Spatial input/ display correspondence in a stereoscopic computer graphic work station. *SIGGRAPH'83 Computer Graphics*, 17 (3), 253-261.

[18] Tendick, F., Jennings, R.W., Tharp, G., & Stark, L. (1993). Sensing and manipulation problems in endoscopic surgery: experiment, analysis, and observation. *Presence*, 2 (1), 66-81.

[19] Ware, C., Arthur, K., & Booth, K.S. (1993). Fish tank virtual reality. *Proceedings of the INTERCHI'93*, 37-42.

[20] Ware, C. (1990). Using hand position for virtual object placement. *The Visual Computer*, 6, 245-253.