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PDRIVE: The Projector-based, Desktop, Reach-In Virtual Environment

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Abstract

This paper presents the Projector-based, Desktop, Reach-In Virtual Environment, or PDRIVE. A PDRIVE user "reaches in" to the virtual environment, which he views through a mirror. Stereo images are generated by two standard, off-the-shelf DLP projectors, which provides a large display and workspace volume at a relatively low cost. Current prototypes use linear polarization for stereo separation and electromagnetically tracked devices for interaction. The PDRIVE is designed to be easy to set up and configure to suit the user's needs, and a variety of projectors, tracking methods, interaction devices, and stereo separation methods can be used in the system.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Virtual Reality;

1. Introduction

In our work on exploring large and complex scientific data sets in VR, we see a growing interest in VR applications from domain specific research partners. Display, tracking and computer hardware has become considerably more accessible in recent years, enabling installation of small but fully functional VR systems, e.g. Fish Tank VR systems [WAB93], at the user's office. We consider this development to be essential for broader application of our work and VR in general since our current and potential users prefer to be independent of external support and VR facilities.

The viability of on-site placement of a "personal" VR system depends on a wide range of factors, of which we will list a few. First, the VR system should be suitable for the target application. In our case, 3D display and 3D tracking devices, each with sufficient quality, are essential to reach the necessary level of interactive, semi-immersive experience. Second, the device must physically fit in the user's workplace. In many situations, only a small amount of desk space can be reserved. Finally, and perhaps most importantly, the total cost of the VR system should meet the user's budget constraints. It is essential to balance the cost of a personal VR installation and the features it provides.

In this paper, we discuss the design and construction of the PDRIVE, our Projector-based, Desktop, Reach-In Virtual Environment (Figure 1). We use two DLP projectors, which provide a substantially larger display size (30 inch)

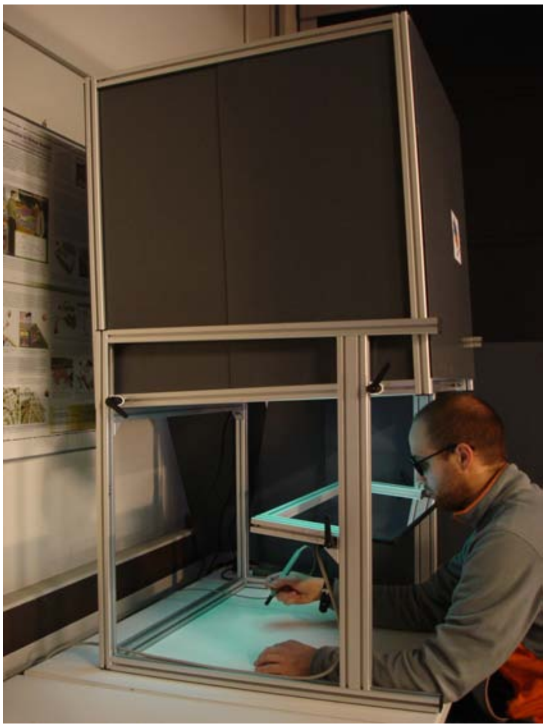

Figure 1: *Current prototype of the PDRIVE, the Projector-based, Desktop, Reach-In Virtual Environment.*

and workspace volume than comparable CRT-based systems. Since we use standard, off-the-shelf projectors we are able to keep the overall system cost low. Furthermore, the PDRIVE is designed to be easy to set up and configure to suit the user's needs, and a variety of projectors, tracking methods, interaction devices, and stereo separation methods can be used in the system

The remainder of the paper is organized as follows. We first overview related work in section 2, after which we introduce our design considerations in section 3. Then, in section 4, we describe the details of our VR system. This includes the selection of projectors and their mounting, as well as the selection of construction and optical material. We describe the actual construction and configuration of our prototypes in section 5, and discuss the resulting system in section 6. Finally, we summarize our results and describe our future work on the prototypes in section 7

2. Related Work

An early, fully-functional reach-in VR system is described in [Sch83]. Here, a CRT monitor is used for stereo display and combined with a semi-transparent mirror to achieve the input/display co-location. Recent extensions and studies on this CRT-based design include the Virtual Workbench [vWSS99] and the Personal Space Station (PSS) [MvL02]. Several similar CRT-based VR systems are currently commercially available, such as the PSS by PS-tech[1], the Reachin Display[2], the Dextroscope[3], the Immersive Touch system[4] and the Immersive Workbench by Sensegraphics[5].

Current CRTs provide a clear, high-resolution image while stereo separation is achieved through active stereo. In practice, this results in 1920x1200 pixel resolution at a refresh rate of 60 Hz per eye. An important limitation of the CRT display monitors used in these systems is a maximum screen diameter of around 22 inches. At comfortable viewing distance, this limits the viewing angle and therefore the volume of the usable co-located VR workspace. At the same time, with the advent of LCD and plasma flat panels and projectors, CRT displays are becoming less readily available.

Large flat panels are suitable to create a large viewing angle (well over 22 inch) and working space, but obtaining stereo on a single display is more difficult. Active stereo is not currently possible on an LCD panel. Currently, stereo LCD solutions exist which use two LCD panels mounted at an angle of 90 degrees, with a large beam-splitter placed at 45 degrees. Stereo separation is achieved through the linear polarization properties of the LCD panel. However, the placement of this beam splitter prevents the creation of a mirror-based co-located VR environment. Another alternative is the use of autostereoscopic panels. An example of such a VR system is the 3d-MIW manufactured by Sensegraphics. It is a mobile system and uses a 15 inch Sharp 3D laptop for its display. However, the ideal combination for a reach-in VR system is both a large display space and a tracked, close range stereo view.

Projector-based systems are widely used in VR community for obtaining large, stereo image displays. Hereld et al. mention important features in building projection based systems, in their case for tiled displays [HJS00]. The use of projectors for co-located input/display in a VR system is not widespread, however. The PARIS system [JSD*00] is one example of a projector-based system. In this system, a single, large active stereo projector is used with a large semi-transparent mirror. The Sensegraphics 3D-LIW, uses a recent Infocus 3D DLP projector, which provides frame-sequential stereo images at a resolution of 800x600 at 60Hz per eye. Both systems provide a large display size, resulting in a wide viewing angle and therefore a large working volume. A side effect is here that the low amount of pixel-per-inch results in a rather low observed image detail. Furthermore, the throw distance needed for the projectors causes the systems to be intrusive and have a large footprint.

3. Design Considerations

We developed the PDRIVE to meet our growing interest in having personal VR systems, both as a convenience during research and development cycles and to make VR more accessible to students and our research partners. Our primary design inspiration was the Personal Space Station [MvL02]. We found the form factor and footprint of such CRT-based systems attractive, but their limited display size and top-heaviness was unattractive. In our opinion, projectors offered the most viable display alternative, due in part to the recent increases in image quality and decreases in price. Therefore, we sought to develop an affordable projector-based system that preserved the basic footprint of CRT-based systems, while providing a larger working volume at usable image quality.

During the design phase, we tried to meet several constraints. The primary constraint was financial. Each VR station should not cost more than 10,000 euro. Secondly, our group has little expertise in the manufacture of VR hardware so we tried to use as many commercially available components as possible. Additionally, we wanted our system to comfortably fit on a desktop, be portable, and be easily maneuverable by two people.

[1] http://www.ps-tech.com
[2] http://www.reachin.se
[3] http://www.dextroscope.com
[4] http://www.immersivetouch.com
[5] http://www.sensegraphics.com

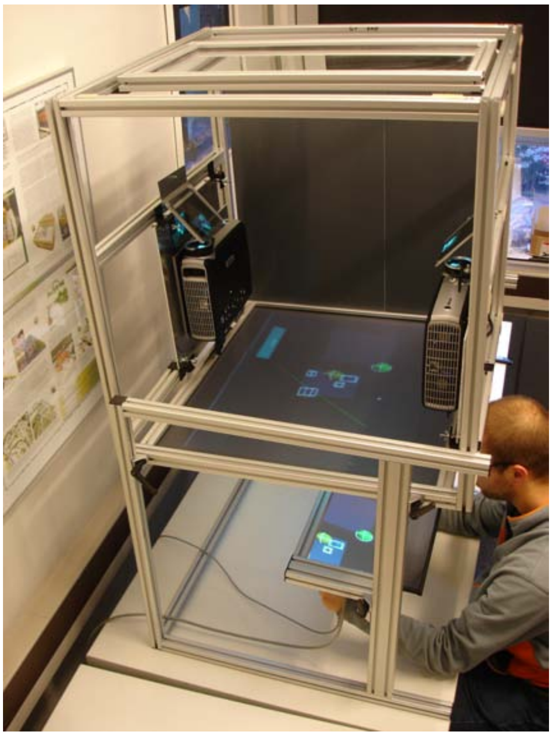

Figure 2: *The inside of the PDRIVE. Two projectors in a mirrored configuration project against an overhead mirror. The image is reflected down onto the screen, which the user views by looking into a second mirror, or* user mirror. *The users hands go behind the second mirror, offering co-location between the user's hands and the virtual objects.*

4. System Description

The PDRIVE is a Projector-based, Desktop, Reach-In Virtual Environment (Figures 1 and 2). We use two projectors mounted in a symmetric configuration. These project onto a mirror, which reflects the images back onto the screen. The user views the screen through a second mirror, the *user mirror*. The user sits with his hands behind the user mirror, which obscures the user's view of his hands, but it provides "reach-in" co-location between the user's hands and objects in the virtual world. In our current prototypes, we mount linear polarization filters in front of each projector for stereo separation. We also use electromagnetic tracking to track the user's interactions and head position.

The PDRIVE has a footprint of 80cm x 75cm and is approximately 1.4m tall, fitting on a standard office desk. One of the strengths of the PDRIVE is its modularity and configurability. The user mirror can be replaced with a semi-transparent mirror for an augmented reality system. Electromagnetic tracking can be replaced by optical tracking. Various off-the-shelf projectors can be used in the system. Haptic arms can be used in the workspace for interaction. These and other options help make the PDRIVE suitable for a variety of applications.

4.1. Projection-Based Display

In our system, we use off-the-shelf projectors in a mirrored configuration (Figure 4). This choice allows us to create stereo images of reasonable quality and alignment for a reasonable price. At the same time, the required physical space in limited.

The common optical alignment in projectors is such that they provide optimal image quality in an ideal situation. That is, a rectangular image is projected if the angle between the flat projection surface and the projector surface is 90 degrees. In addition, a fixed vertical lens shift is used to provide a vertical offset between the lens position and the center of the image. For example, this allows the placement of a projector on a table without tilting it backwards for projecting on a wall screen. If one needs to compensate for any imperfections in the angles or fixed offset, a projector might be tilted. This causes a warping of the projected image. For many projectors, digital keystone compensation may be used to correct for this. Unfortunately, this negatively effects the image quality and resolution.

To achieve a large image display with standard projectors, sufficient throw distance is needed between the projector and the screen. The minimum and maximum distance is determined by the limitations of the zoom and focus optics of the projector. Additional mirror systems can be used to reach this distance in a smaller space, but careful angular alignment is necessary to maintain optimal rectangular images.

To obtain stereo images, two projectors are used in combination with polarization filters. To achieve a usable stereo image, the individual images need to be physically aligned on the display screen. Assuming similar projectors have similar optical factory alignment, if projectors are at the same physical position, an identical image given the same signal is obtained. This is physically not possible without resorting to either digital image correction or the use of optical beam splitters and/or mirrors. In addition, if stereo alignment and distance reducing mirrors are used the alignment process becomes more difficult.

In our design, we take advantage of the fact that the optic alignment is left-right symmetric. That is, if the incoming signal is digitally rotated by 180 degrees, a possible physical position and orientation of the second, flipped projector can be found. A side view of our design is shown in Figure 4. The second projector (Pb) position is symmetric to the position of the first projector (Pa) except for the vertical position which depends directly on the image offset amount. As a result, the second projector is vertically repositioned such that the image center coincides with the other image on screen S'. To ensure the symmetry holds, angles between projectors and the screen S' must be fixed at 90 degrees.

In our approach, we also use a mirror M to reduce the projector to screen distance. We use only one mirror mounted parallel to the projection screen S as we assume that this preserves the 90 degree angle between the projectors and the screen. The positioning of the mirror determines the position of screen S.

We have opted to mechanically align the projector images (see Section 5.3) to preserve the image resolution and achieve the best possible image quality. If a loss of image quality is acceptable or time is a constraint, a software based approach, with the aid of a camera, such as the one proposed by Raskar [Ras00], can be used to align the projector images.

4.2. Stereo separation

Generation of stereo images is an important aspect of a VR system for immersion and presence. This is especially true in "near-field" systems, such as the PDRIVE, where virtual objects are within arm's reach. Popular options for stereo images are active stereo and passive stereo with polarization or INFITEC[6]. In our current PDRIVE prototypes, we have chosen to use passive stereo with linear polarization because of the low cost of the filters and glasses. We have opted against circular polarization due to the amount of crosstalk we experienced in our setup.

One of the chief disadvantages to using linear polarization is crosstalk in the images. Crosstalk, sometimes called ghosting, in a passive stereo system is the undesired visibility of, for example, the left stereo image to the user's right eye. In a system with linear polarization, this is affected by many factors, such as the angle between the polarization filter and the incoming light, the angle between the user's viewpoint and angle of incidence of the polarized light on the screen, the amount the user's head is rotated, and the brightness of the projected images. In general, increasing these factors will lead to an increase in crosstalk.

While crosstalk is present in our system, we can take measures to compensate for it by lowering the brightness of the projectors and adjusting the contrast appropriately. For applications where better stereo separation is required, crosstalk reduction techniques crosstalk techniques, such as those from Smit et al. [SFvL07], or other stereo separation techniques, such as INFITEC, can easily be incorporated into the PDRIVE.

4.3. Ergonomic Configuration

The PDRIVE has many features to make the user's time spent using the system more comfortable. The system is designed to incorporate virtual objects that are co-located with the user's hands allowing him to easily interact with them. The footprint of the system is wider than shoulder width and deeper than arm's reach. This workspace comfortably accommodates most direct interactions, i.e. interactions where the user's hands are co-located with the virtual objects he is interacting with.

[6] http://www.infitec.net

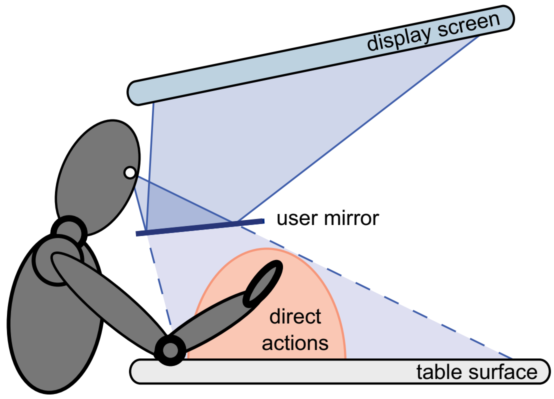

Figure 3: *Ergonomic configuration of workplace, screen and mirror. The placement of the display screen and the user mirror define the size of the workspace and the quality of visual perception (adapted from [MvL02])*

The user mirror is close to the edge of the table, which allows the user to comfortably rest his arms on the table while he interacts with the virtual world (Figure 3). The height of the user mirror is also adjustable to ensure that there is sufficient space for the user's head between the screen and the user mirror. Adjusting the location and orientation of both the user mirror and the screen affects the location of the virtual focus plane. This lets the user select a suitable virtual focus plane for the task at hand.

5. Prototype construction

We have currently built three prototype systems, which have been extensively field tested. The main goal of the prototypes is to provide a flexible configuration of design variations while at the same time be suitable for practical use.

5.1. Basic Construction

For the base construction material, we wanted to use material with good structural integrity and appearance. Furthermore, many parameters in our design were subject to small changes and several sliding and rotating parts were planned. For this reason, we rejected the use of a basic wooden construction and instead selected modular metal components from Item Industrietechnik und Maschinenbau[7]. The basic 30x30 mm aluminum profiles with 6mm wide gutter were prepared at specified lengths from our CAD drawings.

[7] http://www.item.info

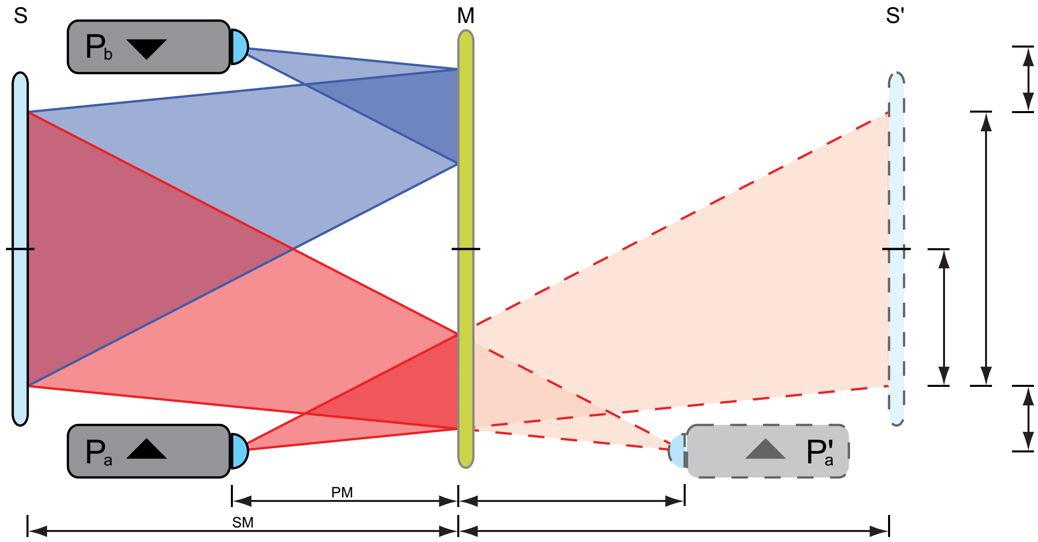

Figure 4: *Layout of optical components to obtain an optimal, factory tuned rectangular image with two projectors. We take advantage of horizontal symmetry of off-the-shelf projector optics, and therefore can flip the second projector. The angle between projector and screen needs to be 90 degrees, and mirror needs to be parallel to the screen*

The frame for our system consists of two separate components: the upper, display box and the lower base stand. Both sections are assembled from the aluminum profiles and various mounting components. The display box rests on top of the base stand and is fixed in position on the front with quick release handles, allowing a flexible reconfiguration of both display height and orientation without the use of tools. The base stand serves to support the display box and also to provide the co-located workspace for the user. One advantage of having two, independent sections to the frame is that the display box can be used as a self-contained stereo projection unit for other applications. Another advantage of the separate display frame is that it is detachable and transportable with minimal re-adjustment of the projectors.

5.2. Mirrors and Screen

We selected rigid projection screens for our prototypes. Both mirrors and the projection screen are easily fixated in the profiles using the 6mm gutter. To avoid the screen or mirrors being excessively deformed due to gravity, they should be as thick and stiff as possible. Since we wanted to mount them in the gutters of the aluminum profiles, though, we limited our selection to mirrors and screens to those with a maximum thickness of 6mm.

The two mirrors (user and overhead) we have chosen are 5mm thick, and they are front-silvered mirrors to provide optimal image quality without image distortions or ghosting. Rubber strips and mounting kit are used to ensure the mirrors remain firmly in place. For the user mirror, we use extra rubber protection to prevent any contact with sharp edges. Quick release handles are also used on the user mirror to allow quick repositioning and reorienting.

The projection screen needs to be a back-projection screen, which preserves polarization. First, as projections and observations are at a large angle to the screen, it is necessary to have the angular screen gain to be as uniform as possible. Second, to avoid possible internal reflections between the screen and any of the two mirrors, we opted for two sided diffuse coating. Our first screen was 5mm thick, but the screen thickness combined with the large projection angles introduced negative diffusion effects resulting in problems with image focus and polarization. We replaced this screen with our current screen, which is 3mm thick and reduces these artifacts.

5.3. Projector Mounting

Mounting the projectors is one of the most intricate details in the construction of our system. To achieve the best possible stereo image quality given our construction, the projectors must be mounted so that the two images from the projectors are rectangular on the screen and perfectly overlap each other. This requires that the screen and overhead mirror be parallel to each other and that the projectors be mounted perpendicularly to the screen. In theory, given the frame dimensions and the screen and mirror positions, it should be possible to calculate the exact position and orientation at which the projectors should be fixed to the frame in order to achieve this optimal image quality. In practice, however, this is difficult to do, and subtle adjustments to the position and orientation of the projectors are necessary to mechan-

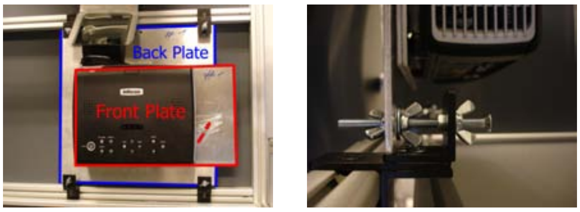

Figure 5: *Left: The projector mount, which consists of two aluminum plates. The projector is fixed to the front plate, which is then fixed to the back plate so that the front plate can be rotated. Right: The brackets used to fix the projector mounts to the frame. These allow each corner of the projector mounts to be transversally translated.*

ically align the projected images on the screen. Therefore, we have chosen to mount the projectors on aluminum plates and attach these plates to the frame so that we can make the necessary adjustments. Figure 5 shows the projector mounts and the brackets used to attach them to the frame.

5.4. Tracking

For tracking in our system, we use Polhemus FASTRAK[8] electromagnetic trackers. We opted for electromagnetic tracking over optical or ultrasonic tracking because it offers reasonable device and head tracking in our system without suffering from occlusions. It is easy to configure and calibrate, and no significant extra processing capacity is needed for the tracking. The use of aluminum in the frame introduces distortion in the tracking data, but this is minimal if the distance between sensors and emitters are kept small and both are kept at a reasonable distance from the frame. See [NMFP98] for a more detailed discussion of the effects of various materials on electromagnetic tracking. Most importantly, the distortion introduced by the aluminum is systematic, i.e. without random noise, so the user is largely unaware of it since his hands are obscured from view. The distortion is most noticeable near the PDRIVE frame on the outer edges of the physical workspace.

We mount the emitter for the FASTRAK system under the viewing mirror at a reasonable distance from the aluminum frame holding the mirror. This places it in close proximity to the user's hands and head, which minimizes measurement error during tracking. Also, placing the emitter under the mirror keeps it out of the user's view and workspace. In order to properly calibrate tracking for viewing and interaction, we must then identify the positions of the mirror, table and the screen relative to the emitter. Finding the position of the table enables us to fix the table as the "ground plane" in the world, and finding the position of the screen and mirror

[8] http://www.polhemus.com

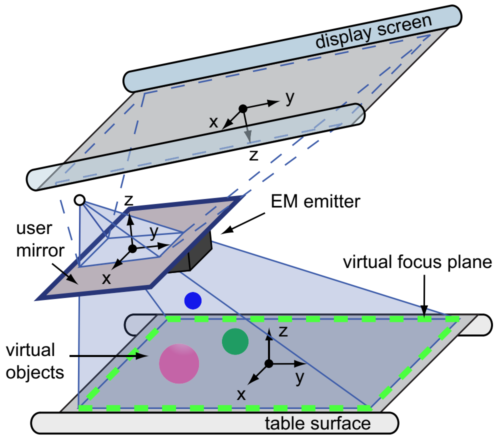

Figure 6: *Coordinate frames used for tracking and tracking setup. The electromagnetic emitter is mounted under the user mirror. During a calibration process, the relation between the coordinate frames for the screen, mirror and table are derived. The relation between the mirror and screen determines the virtual focus plane.*

fixes the viewing frustum. The relationship between the mirror and screen determines the virtual focus plane. The layout of the various coordinate frames of the three spaces is illustrated in Figure 6. In our basic calibration process, we calibrate these coordinate frames by indicating a series of positions with a tracked device on the mirror, screen and table. Once the calibration process is complete, tracking measurements of interaction devices can be converted to the world coordinate frame.

5.5. Operational State

To complete the PDRIVE, additional work and materials are required. The system is driven by a single, standard computer with an LCD monitor that can be used as a terminal screen. The projectors and the LCD monitor are connected to the computer with DVI cables and a DVI splitter. To prevent damage to the surface that the PDRIVE sits on, we place rubber strips underneath the base aluminum profiles. To reduce the effects of ambient light, and to reduce the noise of the projectors, we enclose the upper, projector box. This also requires ventilation to prevent the projectors from overheating and the polarization filters from melting.

6. Results

To date, we have constructed three PDRIVE prototypes. The approximate costs for building one system are given in Table 1. The total cost is about 12,200 euro, but this is largely dependent on the cost of the tracking and the computer to drive the system.

During prototype construction, it took two authors about

Component	Price (euro)
Frame Material	850
Front-Silvered Mirror (2)	700
Back-Projection Screen	350
DLP Projector (2)	2000
Polarization Filters (2)	100
DVI Splitter	200
Electromagnetic Tracking	6000
Computer	1600
LCD Monitor	400
Total	12200

Table 1: *This table lists the costs of the various components of the PDRIVE. All prices are given in euro.*

Figure 7: *PDRIVE ready for transport. The upper, projector box has been placed within the base frame.*

two to three days to get a PDRIVE into an operational state. However, much of this time was spent on last minute design changes, the construction of the projector mounts, and the alignment of the projectors. Now that we have refined the process and finalized most of the design decisions, we estimate that a complete PDRIVE system could be assembled in one day by two graduate students if prefabricated projector mounts and known projectors are used. Extra time should be factored in for the integration and calibration of a tracking system.

The completed PDRIVE systems meet most of our original design requirements. The total system cost of the current prototypes does exceed our original budget of 10,000 euro, but this can be reduced by using a cheaper tracking system. The PDRIVE is entirely assembled out of commercially available components, except for the projector and polarization filter mounts, which we had to construct ourselves. The system fits on a regular office desk, and can even be placed around a user's existing LCD monitor and keyboard to save

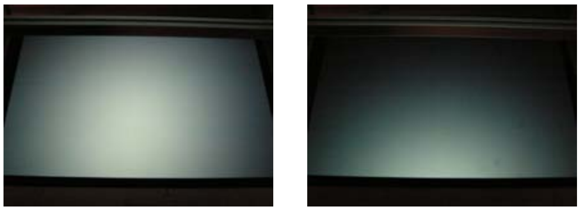

Figure 8: *Variation in image brightness between the back projector (left) and the front projector (right) while projecting a uniform, gray image as seen from the user's point of view with factory default settings for the projectors. Hot spots in both images are clearly visible. See Figure 2 for an illustration of the projector placement. The back projector (left) produces a brighter and more uniform image because the image is being projected "towards" the user. The front projector (right) produces a much darker image with a hot spot close to the user because the image is being projected "away" from the user.*

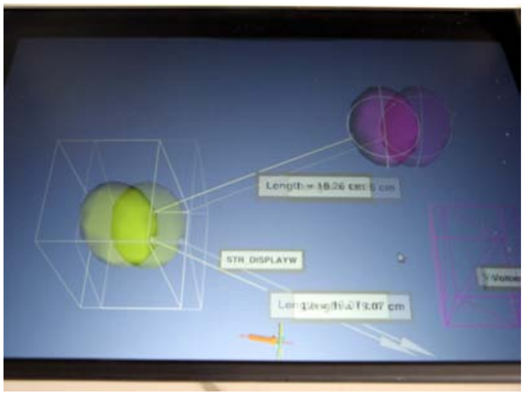

Figure 9: *Stereo image photographed from the user's perspective under normal office lighting conditions, after adjustments have been made to the projectors' brightness and contrast settings.*

space. The upper, projector box can be removed and placed within the lower frame for transport, and the system is easily lifted and moved by two people. The total weight of a complete system is about 30 kilograms.

The design of the PDRIVE provides a large and comfortable workspace for the user. The adjustability of various components lets the user choose settings that are suitable for him. The visible image is approximately 30 inches (60cm x 45cm) on the screen. This large screen size provides a virtual workspace that is larger than the physical workspace, and the physical workspace is large enough for most user interactions.

One of the challenges posed by our design is the difference between the angles of incidence from the two projectors. The back projector projects "towards" the user and the front projector projects "away" from the user. This means that the location of the hot spots and the overall brightness of the images generated by each projector appear different from the user's perspective (Figure 8), which is caused by the non-uniform screen gain. However, we can compensate reasonably well for this by tuning the brightness and contrast of each projector (Figure 9). In the future, we would like to use a two stage rendering process to further reduce these effects.

7. Conclusion and Future Work

In this paper, we introduced our Projector-based, Desktop, Reach-In Virtual Environment, or PDRIVE. The virtual environment is viewed through a mirror, which obscures the user's view of his hands (Figure 3). This provides "reach-in" co-location between the user's hands and the virtual objects. To create the stereo images, the PDRIVE uses two standard, off-the-shelf DLP projectors, which are mounted in the upper part of the frame in a symmetric configuration. They project onto an overhead mirror, which reflects the images down onto the screen (Figures 2 and 4). The total cost of our recent complete prototype, including a computer to drive it, is about 12,200 euro (Table 1).

The PDRIVE has a footprint of 80cm x 75cm, is approximately 1.4m tall and fits on a regular table or desk, see Figure 1. It offers a large and comfortable VR workspace for the user. The footprint gives sufficient room for most interactions, and the large screen size (30 inch image size) provides a virtual workspace that is larger than the physical workspace. The adjustability of the user mirror and the screen lets the user choose a comfortable virtual focus plane, while ensuring there is enough space for his head between the screen and the mirror. If space is an issue, the PDRIVE can be placed over the user's existing workplace, with the user mirror raised out of the way. Furthermore, without a heavy CRT monitor, the PDRIVE is stable, reasonably lightweight and portable. For transport, the top projector box fits within the lower frame.

The current PDRIVE allows for many enhancements and is easily customizable. Our current prototypes use linear polarization filters to separate the stereo images and an electromagnetic tracking system. These components, and others like the user mirror, interaction devices, and projectors, can be customized to meet the requirements of most Fish Tank VR applications. In the future, we would like to further refine and vary these various components.

Our main two interests here are to improve the quality of stereo imagery and tracking. For improved stereo image quality, we plan to evaluate hardware solutions such as higher quality projectors, screens and stereo filters. We also plan to model screen properties, image brightness and crosstalk, which can help us to develop specific software-based image rendering and calibration techniques. For improved tracking, we would like to improve the calibration process, especially by automatically tracking the positions of the movable mirror and screen. By combining facilities for automated tracking and image calibration, we expect the VE quality to be improved and set up time to be reduced.

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