Towards Spontaneous Interaction with the Perceptive Workbench, a Semi-Immersive Virtual Environment[*]

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Abstract

The Perceptive Workbench enables a spontaneous and unimpeded interface between the physical and virtual worlds. It uses vision-based methods for interaction that eliminate the need for wired input devices and wired tracking. Objects are recognized and tracked when placed on the display surface. Through the use of multiple infrared light sources, the object's 3D shape can be captured and inserted into the virtual interface. This ability permits spontaneity since either preloaded objects or those objects selected on the spot by the user can become physical icons. Integrated

into the same vision-based interface is the ability to identify 3D hand position, pointing direction, and sweeping arm gestures. Such gestures can enhance selection, manipulation, and navigation tasks. In this paper, the Perceptive Workbench is used for augmented reality gaming and terrain navigation applications, which demonstrate the utility and flexibility of the interface.

1. Introduction

Until now, we have interacted with computers mostly by using devices that are constrained by wires. Typically, the wires limit the distance of movement and inhibit freedom of orientation. In addition, most interactions are indirect. The user moves a device as an analogue for the action to be created in the display space. We envision an interface without these restrictions. It is untethered; accepts direct, natural gestures; and is capable of spontaneously accepting as interactors any objects we choose. In conventional 3D interaction, the devices that track position and orientation are still usually tethered to the machine by wires. Devices, such as pinch gloves, that permit the user to experience a more natural-seeming interface often do not perform as well and are less preferred with users, than simple handheld devices with buttons [Kessler95, Seay99]. Pinch gloves carry assumptions about the position of the user's hand and fingers with respect to the tracker. Of course, users' hands differ in size and shape, so the assumed tracker position must be recalibrated for each user. This is hardly ever done. Also, the glove interface causes subtle changes to recognized hand gestures. The result is that fine manipulations can be imprecise, and the user comes away with the feeling that the interaction is slightly off in an indeterminate way. If we can recognize gestures directly, we take into account the difference in hand sizes and shapes.

An additional problem is that any device held in the hand can become awkward while gesturing. We have found this even with a simple pointing device, such as a stick with a few buttons

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[Seay99] (see Figure 1). Also a user, unless fairly skilled, often has to pause to identify and select buttons on the stick. With accurately tracked hands most of this awkwardness disappears. We are adept at pointing in almost any direction and can quickly pinch fingers, for example, without looking at them.
Finally, physical objects are often natural interactors (such as phicons [Ullmer97]). However, with current systems these objects must be inserted in advance or specially prepared. One would like the system to accept objects that one chooses spontaneously for interaction.

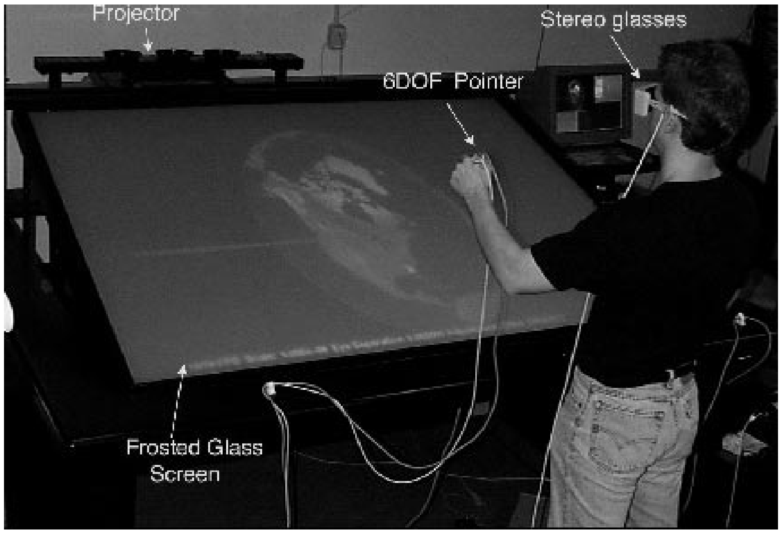


Figure 1: A user interacting with Georgia Tech's Virtual Workbench using a 6DoF pointer.

In this paper we discuss methods for producing more seamless interaction between the physical and virtual environments through the creation of the Perceptive Workbench. The system is then applied to an augmented reality game and a terrain navigating system. The Perceptive Workbench can reconstruct 3D virtual representations of previously unseen real-world objects placed on its surface. In addition, the Perceptive Workbench identifies and tracks such objects as they are manipulated on the desk's surface and allows the user to interact with the augmented environment through 2D and 3D gestures. These gestures can be made on the plane of the desk's surface or in the 3D space above the desk. Taking its cue from the user's actions, the Perceptive Workbench switches between these modes automatically, and all interaction is controlled through computer vision, freeing the user from the wires of traditional sensing techniques.

2. Related Work

While the Perceptive Workbench [Leibe00] is unique in its extensive ability to interact with the physical world, it has a rich heritage of related work [Arai95, Bimber99, Coquillart99, Kobayashi98, Krueger91, Krueger95, May99, Rekimoto97, Schmalstieg99, Seay99, Ullmer97, Underkoffler98, vdPol99, Wellner93]. Many augmented desk and virtual reality designs use tethered props, tracked by electromechanical or ultrasonic means, to encourage interaction through manipulation and gesture [Bolt92, Bimber99, Coquillart99, Schmalstieg99, Seay99, Sturman92, vdPol99]. Such designs tether the user to the desk and require the time-consuming ritual of donning and doffing the appropriate equipment.

Fortunately, the computer vision community has taken up the task of tracking the user's hands and identifying gestures. While generalized vision systems track the body in room and desk-based scenarios for games, interactive art, and augmented environments [Bobick99, Wren97], reconstruction of fine hand detail involves carefully calibrated systems and is computationally intensive [Rehg94]. Even so, complicated gestures such as those used in sign language [Starner98, Vogler98] or the manipulation of physical objects [Sharma97] can be recognized. The Perceptive Workbench uses computer vision techniques to maintain a wireless interface.

Most directly related to the Perceptive Workbench, Ullmer and Ishii's "Metadesk" [Ullmer97] identifies and tracks objects placed on the desk's display surface using a near-infrared computer vision recognizer, originally designed by Starner. Unfortunately, since not all objects reflect infrared light and infrared shadows are not used, objects often need infrared reflective "hot mirrors" placed in patterns on their bottom surfaces to aid tracking and identification. Similarly, Rekimoto and Matsushita's "Perceptual Surfaces" [Rekimoto97] employ 2D barcodes to identify objects held against the "HoloWall" and "HoloTable." In addition, the HoloWall can track the user's hands (or other body parts) near or pressed against its surface, but its potential recovery of the user's distance from the surface is relatively coarse compared to the 3D pointing gestures of the Perceptive Workbench. Davis and Bobick's SIDEshow [Davis98] is similar to the Holowall except that it uses cast shadows in infrared for full-body 2D gesture recovery. Some augmented desks have cameras and projectors above the surface of the desk and are designed to augment the process of handling paper or interacting with models and widgets through the use of fiducials or barcodes [Arai95, Kobayashi98, Underkoffler98, Wellner93]. Krueger's VIDEODESK [Krueger91], an early desk-based system, used an overhead camera and a horizontal visible light table (for high contrast) to provide hand gesture input for interactions displayed on a monitor on the far side of the desk. In contrast with the Perceptive Workbench, none of these systems address the issues of introducing spontaneous 3D physical objects into the virtual environment in real-time and combining 3D deictic (pointing) gestures with object tracking and identification.

3. Apparatus

The display environment for the Perceptive Workbench is based on Fakespace's immersive workbench, consisting of a wooden desk with a horizontal frosted glass surface on which a stereoscopic image can be projected from behind the Workbench (see Figure 1).

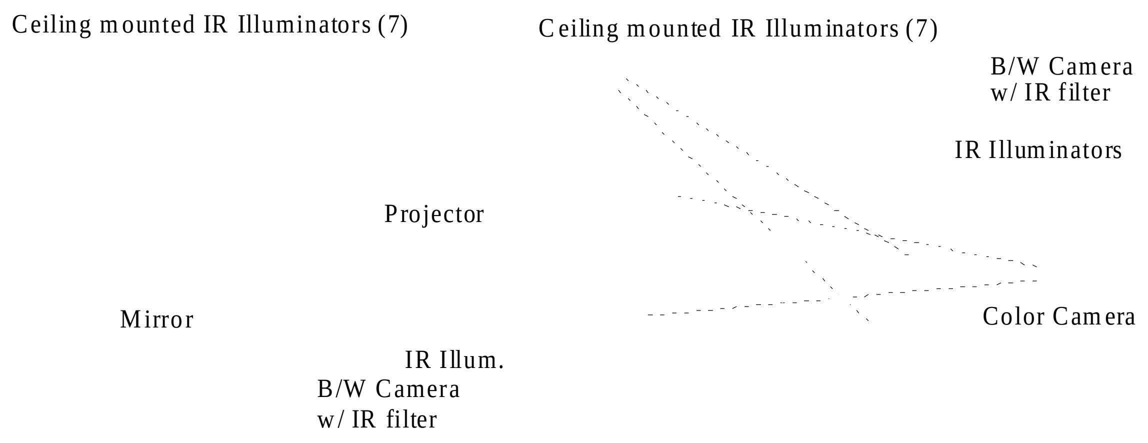


Figure 2: Light and camera positions for the Perceptive Workbench.
The top view shows how shadows are cast and the 3D arm position is tracked.

We placed a standard monochrome surveillance camera under the projector that watches the desk surface from underneath (see Figure 2). A filter placed in front of the camera lens makes it insensitive to visible light and to images projected on the desk's surface. Two infrared illuminators placed next to the camera flood the surface of the desk with infrared light that is reflected toward the camera by objects placed on the desk's surface (Figure 3).

A ring of seven similar light-sources is mounted on the ceiling surrounding the desk (Figure 2). Each computer-controlled light casts distinct shadows on the desk's surface based on the objects on the table (Figure 5a). A second camera, this one in color, is placed next to the desk to provide a side view of the user's arms (Figure 6a). This side camera is used solely for recovering 3D pointing gestures.

We decided to use near-infrared light since it is invisible to the human eye. Thus, illuminating the scene with it does not interfere with the user's interaction. Neither the illumination from the IR light sources underneath the table, nor the shadows cast from the overhead lights can be observed by the user. On the other hand, IR light can still be seen by most standard CCD cameras. This makes it a very inexpensive method for observing the interaction. In addition, by equipping the camera with an infrared filter, the camera image can be analyzed regardless of changes in (visible) scene lighting.

All vision processing is done on two SGI R10000 O2s (one for each camera), which communicate with a display client on an SGI Onyx via sockets. However, the vision algorithms could also be run on one SGI with two digitizer boards or be implemented using inexpensive, semi-custom signal-processing hardware.
We use this setup for three different kinds of interaction which will be explained in more detail in the following sections: recognition and tracking of objects placed on the desk surface based on their contour, full 3D reconstruction of object shapes on the desk surface from shadows cast by the ceiling light-sources, and recognition and quantification of hand and arm gestures.

For display on the Perceptive Workbench, we use the Simple Virtual Environment Toolkit (SVE), a graphics and sound library developed by the Georgia Tech Virtual Environments Group [Kessler00]. SVE permits us to rapidly prototype applications used in this work. In addition we use the workbench version of VGIS, a global terrain visualization and navigation system [Lindstrom96] as an application for interaction using hand and arm gestures. The workbench version of VGIS has stereoscopic rendering and an intuitive interface for navigation [Wartell99]. Both systems are built on OpenGL and have both SGI and PC implementations.

4. Object Tracking & Recognition

As a basic building block for our interaction framework, we want to enable the user to manipulate the virtual environment by placing objects on the desk surface. The system should recognize these objects and track their positions and orientations while they are being moved over the table. The user should be free to pick any set of physical objects he wants to use.

The motivation behind this is to use physical objects in a graspable user interface [Fitzmaurice95]. Physical objects are often natural interactors (such as "phicons" [Ullmer97]). They can provide physical handles to control the virtual application in a way that is very intuitive for the user [Ishii97]. In addition, the use of objects encourages two-handed direct manipulation and allows parallel input specification, thereby improving the communication bandwidth with the computer. [Fitzmaurice95, Ishii97].

To achieve this goal, we use an improved version of the technique described in Starner *et al.* [Starner00]. The underside of the desk is illuminated by two near-infrared light-sources (Figure 2). Every object close to the desk surface (including the user's hands) reflects this light and can be seen by the camera under the display surface (Figure 3). Using a combination of intensity thresholding and background subtraction, we extract interesting regions of the camera image and analyze them. The resulting blobs are classified as different object types based on a set of features, including area, eccentricity, perimeter, moments, and the contour shape.

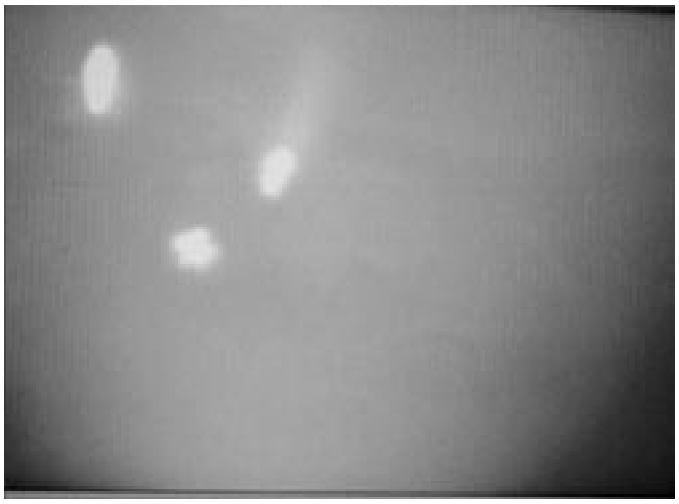


Figure 3: Image of reflection from the IR lights underneath the desk, as seen from the infrared camera.

There are several complications due to the hardware arrangement. The foremost problem is that our two light sources under the table can only provide a very uneven lighting over the whole desk surface, bright in the middle, and getting weaker toward the borders. In addition, the light rays are not parallel, and the reflection on the mirror surface further exacerbates this effect. As a result, the perceived sizes and shapes of objects on the desk surface can vary depending on position and orientation. Finally, when the user moves an object, the reflection from his hand can also add to the perceived shape. This makes it necessary to use an additional stage in the recognition process that matches recognized objects to objects known to be on the table and that can filter out wrong classification or even handle complete loss of information about an object for several frames.

In this work, we are using the object recognition and tracking capability mainly for "cursor objects". Our focus is on fast and accurate position tracking, but the system may be trained on a different set of objects to be used as navigational tools or physical icons [Ullmer97]. A future project will explore different modes of interaction based on this technology.

5. Deictic Gesture Tracking

Hand gestures can be roughly classified into symbolic (iconic, metaphoric, and beat) and deictic (pointing) gestures. Symbolic gestures carry an abstract meaning that may still be recognizable in iconic form in the associated hand movement. Without the necessary cultural context, however, the meaning may be arbitrary. Examples for symbolic gestures include most conversational gestures in everyday use, and whole gesture languages, for example, American Sign Language. Previous work by Starner [Starner98] has shown that a large set of symbolic gestures can be distinguished and recognized from live video images using hidden Markov models.
Deictic gestures, on the other hand, are characterized by a strong dependency on location and orientation of the performing hand. Their meaning is determined by the location at which a finger is pointing, or by the angle of rotation of some part of the hand. This information acts not only as a symbol for the gesture's interpretation, but also as a measure of by how much the corresponding action should be executed or to which object it should be applied.

For navigation and object manipulation in a virtual environment, many gestures are likely to have a deictic component. It is usually not enough to recognize that an object should be rotated, but we will also need to know the desired amount of rotation. For object selection or translation, we want to specify the object or location of our choice just by pointing at it. For these cases, gesture recognition methods that only take the hand shape and trajectory into account will not be sufficient. We need to recover 3D information about the user's hand and arm in relation to his body.

In the past, this information has largely been obtained by using wired gloves or suits, or magnetic trackers [Bolt92, Bimber99]. Such methods provide sufficiently accurate results but rely on wires and have to be tethered to the user's body, or to specific interaction devices, with all the aforementioned problems. Our goal is to develop a purely vision-based architecture that facilitates unencumbered 3D interaction.

With vision-based 3D tracking techniques, the first issue is to determine which information in the camera image is relevant, *i.e.* which regions represent the user's hand or arm. This task is made even more difficult by variation in user clothing or skin color and by background activity. Although typically only one user interacts with the environment at a given time using traditional methods of interaction, the physical dimensions of large semi-immersive environments such as the workbench invite people to watch and participate.

In a virtual workbench environment, there are few places where a camera can be placed to provide reliable hand position information. One camera can be set up next to the table without overly restricting the available space for users, but if a similar second camera were to be used at this location, either multi-user experience or accuracy would be compromised. We have addressed this problem by employing our shadow-based architecture (as described in the hardware section). The user stands in front of the workbench and extends an arm over the surface. One of the IR light-sources mounted on the ceiling to the left of, and slightly behind the user, shines its light on the desk surface, from where it can be seen by the IR camera under the projector (see Figure 4). When the user moves his arm over the desk, it casts a shadow on the desk surface (see Figure 5a). From this shadow, and from the known light-source position, we can calculate a plane in which the user's arm must lie.

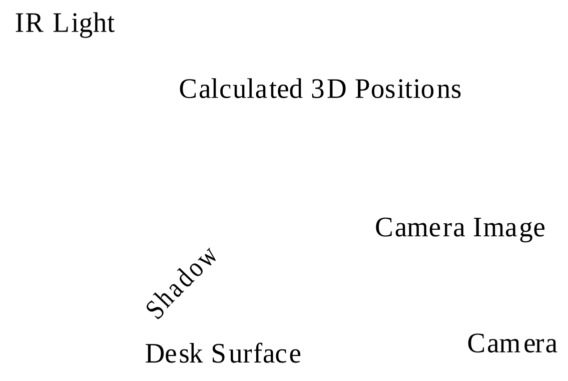


Figure 4: Principle of pointing direction recovery.

Simultaneously, the second camera to the right of the table (Figure 4 and Figure 6a) records a side view of the desk surface and the user's arm. It detects where the arm enters the image and the position of the fingertip. From this information, it extrapolates two lines in 3D space, on which the observed real-world points must lie. By intersecting these lines with the shadow plane, we get the coordinates of two 3D points, one on the upper arm, and one on the fingertip. This gives us the user's hand position, and the direction in which the user is pointing. As shown in Figure 12a, this information can be used to project a icon for the hand position and a selection ray in the workbench display.

Obviously, the success of the gesture tracking capability relies very strongly on how fast the image processing can be done. It is therefore necessary to use simple algorithms. Fortunately, we can make some simplifying assumptions about the image content.
We must first recover arm direction and fingertip position from both the camera and the shadow image. Since the user is standing in front of the desk and the user's arm is connected to the user's body, the arm's shadow should always touch the image border. Thus our algorithm exploits intensity thresholding and background subtraction to discover regions of change in the image and

searches for areas in which these touch the front border of the desk surface (which corresponds to the top border of the shadow image or the left border of the camera image). It then takes the middle of the touching area as an approximation for the origin of the arm (Figure 5b and Figure 6b). For simplicity we will call this point the "shoulder", although in most cases it is not. Tracing the contour of the shadow, the algorithm searches for the point that is farthest away from the shoulder and takes it as the fingertip. The line from the shoulder to the fingertip reveals the 2D direction of the arm.

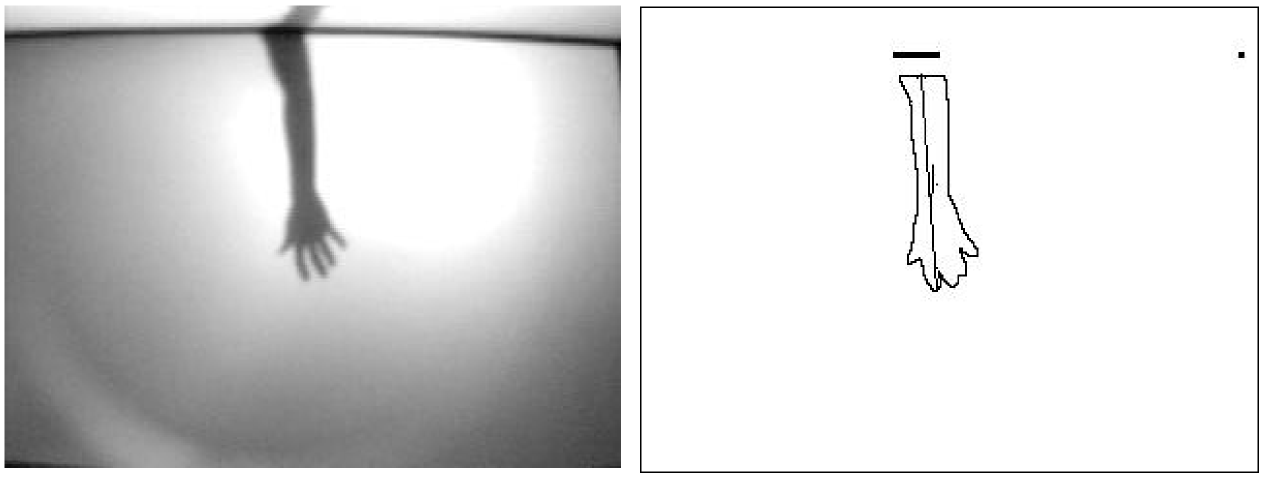


Figure 5: (a) Arm shadow from overhead IR lights;
(b) resulting contour with recovered arm direction.

In our experiments, the point thus obtained was coincident with the pointing fingertip in all but a few extreme cases (such as the fingertip pointing straight down at a right angle to the arm). The method does not depend on a pointing gesture, but also works for most other hand shapes, including but not restricted to, a hand held horizontally, vertically or in a fist. These shapes may be distinguished by analyzing a small section of the side camera image and may be used to trigger specific gesture modes in the future.

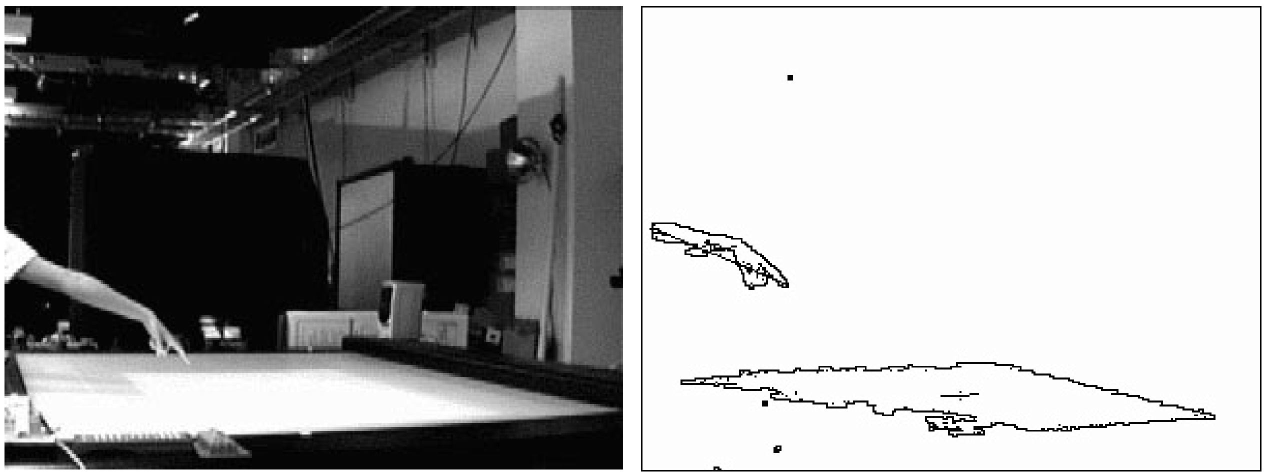


Figure 6: (a) image from side camera; (b) arm contour (from similar image) with recovered arm direction.

The computed arm direction is correct as long as the user's arm is not overly bent (see Figure 6). In such cases, the algorithm still connected shoulder and fingertip, resulting in a direction somewhere between the direction of the arm and the one given by the hand. Although the absolute resulting pointing position did not match the position towards which the finger was pointing, it still managed to capture the trend of movement very well. Surprisingly, the technique is sensitive enough such that the user can stand at the desk with his arm extended over the surface and direct the pointer simply by moving his index finger, without arm movement.

Limitations

The architecture used poses several limitations. The primary problem with the shadow approach is finding a position for the light source that can give a good shadow of the user's arm for a large set of possible positions, while avoiding capture of the shadow from the user's body. Since the area visible to the IR camera is coincident with the desk surface, there are necessarily regions where the shadow is not visible in, touches, or falls outside of the borders. Our solution to this problem is to switch automatically to a different light source whenever such a situation is detected, the choice of the new light source depending on where the shadows touched the border. By choosing overlapping regions for all light sources, we can keep the number of light source switches to a necessary minimum. In practice, four light sources in the original set of seven were enough to cover the relevant area of the desk surface. However, an additional spotlight, mounted directly overhead of the desktop, has been added to provide more direct coverage of the desktop surface.

Another problem can be seen in Figure 6b, where segmentation based on color background subtraction detects both the hand and the change in the display on the workbench. A more recent implementation replaces the side color camera with an infrared spotlight and a monochrome camera equipped with an infrared-pass filter. By adjusting the angle of the light to avoid the surface of the desk or any other close objects, the user's arm is illuminated and made distinct from the background and changes in the workbench's display do not affect the tracking.

A bigger problem is caused by the actual location of the side camera. If the user extends both of his arms over the desk surface, or if more than one user tries to interact with the environment at the same time, the images of these multiple limbs can overlap and be merged to a single blob. As a consequence, our approach will fail to detect the hand positions and orientations in these cases. A more sophisticated approach using previous position and movement information could yield more reliable results, but we chose, at this first stage, to accept this restriction and concentrate on high frame rate support for one-handed interaction. This may not be a serious limitation for a single user for certain tasks; a recent study shows that for a task normally requiring two hands in a real environment, users have no preference for one versus two hands in a virtual environment that does not model effects such as gravity and inertia [Seay99].

6. 3D Reconstruction

To complement the capabilities of the Perceptive Workbench, we want to be able to insert real objects into the virtual world and to share them with other users at different locations. An example application for this could be a telepresence or computer-supported collaborative work (CSCW) system. Instead of verbally describing an object, the user would be able to quickly create a 3D reconstruction and send it to his co-workers (see Figure 7). For this, it is necessary to design a reconstruction mechanism that does not interrupt the interaction. Our focus is providing an almost instantaneous visual cue for the object as part of the interaction, not necessarily on creating a highly accurate model.

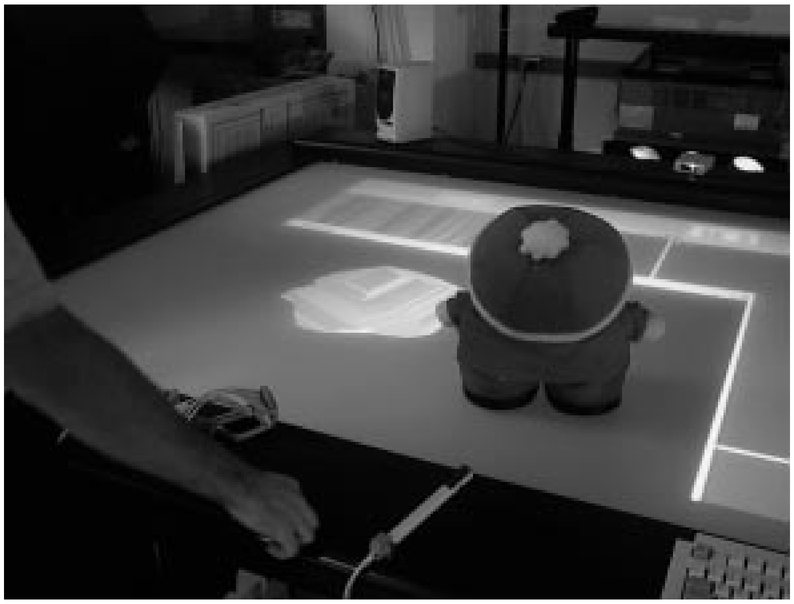


Figure 7: Real object inserted into the virtual world. The figure shows a reconstruction of the doll in the foreground.

Several methods have been designed to reconstruct objects from silhouettes [Srivastava90, Sullivan98] or dynamic shadows [Daum98] using either a moving camera or light-source on a known trajectory or a turntable for the object [Sullivan98]. Several systems have been developed for the reconstruction of relatively simple objects, including some commercial systems.

However, the necessity to move either the camera or the object imposes severe constraints on the working environment. To reconstruct an object with these methods, it is usually necessary to interrupt the user's interaction with it, take the object out of the user's environment, and place it into a specialized setting (sometimes in a different room). Other approaches make use of multiple cameras from different view points to avoid this problem at the expense of more computational power to process and communicate the results.
In this project, using only one camera and the infrared light sources, we analyze the shadows cast on the object from multiple directions (see Figure 8). As the process is based on infrared light, it can be applied independently of the lighting conditions and without interfering with the user's natural interaction with the desk.

The existing approaches to reconstruct shape from shadows or silhouettes can be divided into two camps. The *volume approach*, pioneered by Baumgart [Baumgart74], intersects view volumes to create a representation for the object. Common representations for the resulting model are polyhedra [Baumgart74, Connolly89], or octrees [Srivastava90, Chien86]. The *surface approach* reconstructs the surface as the envelope of its tangent planes. It has been realized in several systems [Boyer96, Seales95]. Both approaches can be combined, as in Sullivan's work

[Sullivan98], which uses volume intersection to create an object and then smoothes the surfaces with splines.

We have chosen to use a volume approach to create polyhedral reconstructions for several reasons. We want to create models that can be used instantaneously in a virtual environment. Our focus is not on getting a photorealistic reconstruction, but on creating a quick low polygon-count model for an arbitrary real-world object in real-time, without interrupting the ongoing interaction. Polyhedral models offer significant advantages over other representations, such as generalized cylinders, superquadrics, or polynomial splines. They are simple and computationally inexpensive, Boolean set operations can be performed on them with reasonable effort, and most current VR engines are optimized for fast rendering of polygonal scenes. In addition, polyhedral models are the basis for many later processing steps. If desired, they can still be refined with splines using a surface approach.

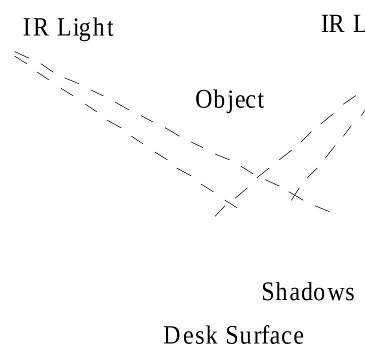


Figure 8: Principle of the 3D reconstruction.

To obtain the different views, we mounted a ring of seven infrared light sources in the ceiling, each one of which is switched independently by computer control. The system detects when a new object is placed on the desk surface, and the user can initiate the reconstruction by touching a virtual button rendered on the screen (Figure 12). This action is detected by the camera, and, after only one second, all shadow images are taken. In another second, the reconstruction is complete (Figure 11), and the newly reconstructed object is part of the virtual world.

Our approach is fully automated and does not require any special hardware (*e.g.* stereo cameras, laser range finders, structured lighting, *etc.*). The method is extremely inexpensive, both in hardware and in computational cost. In addition, there is no need for extensive calibration, which is usually necessary in other approaches to recover the exact position or orientation of the object in relation to the camera. We only need to know the approximate position of the light-sources (+/- 2 cm), and we need to adjust the camera to reflect the size of the display surface, which must be done only once. Neither the camera, light-sources, nor the object are moved during the reconstruction process. Thus recalibration is unnecessary. We have substituted for all mechanical moving parts, which are often prone to wear and imprecision, by a series of light beams from known locations.

An obvious limitation for this approach is that we are confined to a fixed number of different views from which to reconstruct the object. The turntable approach, on the other hand, allows the system to take an arbitrary number of images from different view points. However, Sullivan's work [Sullivan98] and our experience with our system have shown that even for quite complex objects, usually seven to nine different views are enough to get a reasonable 3D model of the object. Note that the reconstruction uses the same hardware as the deictic gesture tracking capability discussed in the previous section. Thus, it comes at no additional cost.

The speed of the reconstruction process is mainly limited by the switching time of the light sources. Whenever a new light-source is activated, the image processing system has to wait for several frames to receive a valid image. The camera under the desk records the sequence of shadows cast by an object on the table when illuminated by the different lights. Figure 9 shows two series of contour shadows extracted from two sample objects by using different IR sources. By approximating each shadow as a polygon (not necessarily convex) [Rosin95], we create a set of polyhedral "view cones", extending from the light source to the polygons. The intersection of these cones creates a polyhedron that roughly contains the object. Figure 10 shows some more shadows with the resulting polygons and a visualization of the intersection of polyhedral cones.

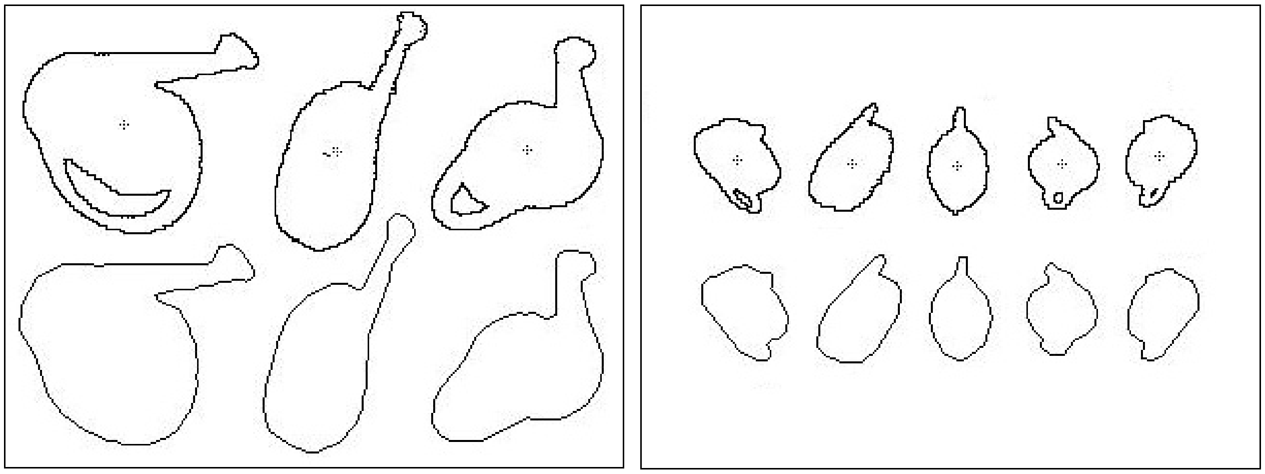


Figure 9: Shadow contours (top) and interpolated polygons (bottom) from a watering can (left) and a teapot (right). The current version of our software does not handle holes in the contours yet.

Intersecting non-convex polyhedral objects is a very complex problem, further complicated by numerous special cases that have to be taken care of. Fortunately, this problem has already been exhaustively researched, and solutions are available [Mantyla88]. For the intersection calculations in our application, we used Purdue University's TWIN Solid Modeling Library [TWIN95].

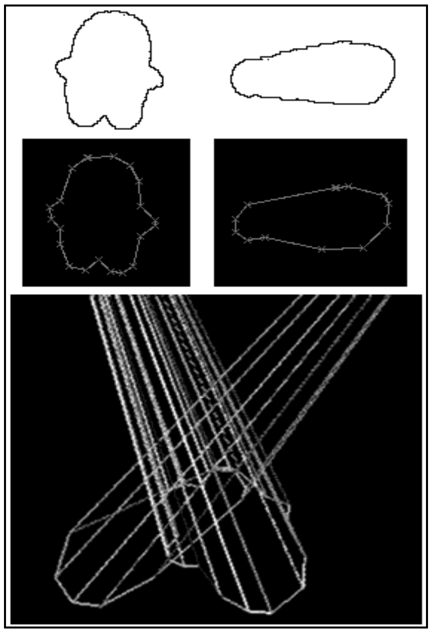


Figure 10: Steps of the 3D reconstruction of the doll from Figure 7, including extraction of contour shapes from shadows and intersection of multiple view cones (bottom).

Figure 12b shows a freshly reconstructed model of a watering can placed on the desk surface. The same model can be seen in more detail in Figure 11, along with the reconstruction of a teapot. The colors were chosen to highlight the different model faces by interpreting the face normal as a vector in RGB color space.

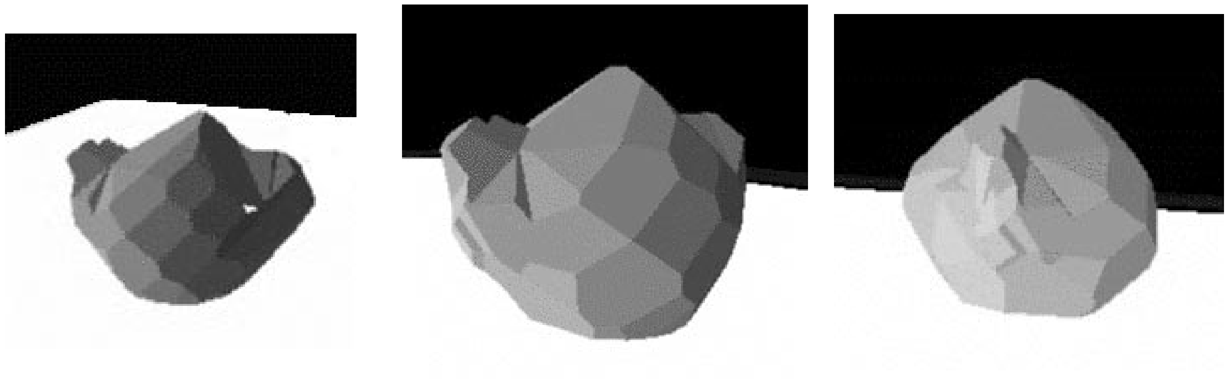


Figure 11: 3D reconstruction of the watering can seen in Figure 10 (top) and a teapot (bottom). The colors are chosen to highlight the model faces.

Limitations

An obvious limitation to our approach is that not every non-convex object can be exactly reconstructed from its silhouettes or shadows. The closest approximation that can be obtained with volume intersection is its "visual hull", *i.e.* the volume enveloped by all the possible circumscribed view cones [Laurentini94]. But even for objects with a polyhedral visual hull an unbounded number of silhouettes may be necessary for an exact reconstruction [Laurentini97]. In practice, we can get sufficiently accurate models for a large variety of real-world objects, even from a relatively small number of different views.

Exceptions are spherical or cylindrical objects. The quality of reconstruction for these objects depends largely on the number of available views. With only seven light-sources, the resulting model will appear faceted. This problem can be solved by either adding more light-sources, or by improving the model with the help of splines.

Apart from this, the accuracy by which objects can be reconstructed is bounded by another limitation of our architecture. All our light-sources are mounted to the ceiling. From this point of view they cannot provide full information about the object's shape. There is a pyramidal "blind spot" above all horizontal flat surfaces that the reconstruction cannot eliminate. The slope of these pyramids depends on the angle between the desk surface and the rays from the light-sources. For our current hardware setting, this angle ranges between 37° and 55°, depending on the light-source. Only structures with a greater slope will be reconstructed entirely without error. This problem is intrinsic to the method and does also occur with the turntable approach, but on a much smaller scale.

We expect that we can greatly reduce the effects of this error by using the image from the side camera and extracting an additional silhouette of the object from this point of view. This will help to keep the error angle well below 10°. Calculations based on the current position of the side camera (optimized for the gesture recognition) promise an error angle of only 7°.

In the current version of our software, an additional error is introduced through the fact that we are not yet handling holes in the shadows. But this is merely an implementation issue, which will be resolved in a future extension to our project.

7. Performance Analysis

Object and Gesture Tracking

Both object and gesture tracking perform at a stable 12-18 frames per second. Frame rate depends on the number of objects on the table and the size of the shadows, respectively. Both techniques are able to follow fast motions and complicated trajectories. Latency is currently 0.25-0.33 seconds, including display lag (an acceptable threshold for 3D object selection and manipulation tasks is typically around 0.075-0.100 seconds [Ware94, Watson98]). Surprisingly, this level of latency seems still adequate for most (navigational) pointing gestures in our current applications. Since the user is provided with continuous feedback about his hand and pointing position, and most navigation controls are relative rather than absolute, the user adapts his behavior readily to the system. With object tracking, the physical object itself can provide the user with adequate tactile feedback as the system catches up with the user's manipulations. In general, since the user is moving objects across a very large desk surface, the lag is noticeable but rarely troublesome in the current applications.

Even so, we expect that simple improvements in the socket communication between the vision and rendering code and in the vision code itself will improve latency significantly. For the terrain navigation task below, rendering speed provides a limiting factor. However, Kalman filters may compensate for render lag and will also add to the stability of the tracking system.

3D Reconstruction

Calculating the error from the 3D reconstruction process requires choosing known 3D models, performing the reconstruction process, aligning the reconstructed model and the ideal model, and calculating an error measure. For simplicity, a cone and pyramid were chosen. The centers of mass of the ideal and reconstructed models were set to the same point in space, and their principal axes were aligned.

To measure error, we used Cignoni *et al*'s Metro tool [Cignoni98]. It approximates the real distance between the two surfaces by choosing a set of (100,000-200,000) points on the reconstructed surface, and then calculating the two-sided distance (Hausdorff distance) between each of these points and the ideal surface. This distance is defined as

$$\max\left(E(S1,S2),E(S2,S1)\right)$$

with E(S1,S2) denoting the one-sided distance between the surfaces S1 and S2:

$$E(S1,S2)=\max_{p\in S1}\left(dist(p,S2)\right)=\max_{p\in S1}\left(\min_{p'\in S2}\left(dist(p,p')\right)\right)$$

The Hausdorff distance directly corresponds to the reconstruction error. In addition to the maximum distance, we also calculated the mean and mean square distances. Table 1 shows the results. In these examples, the relatively large maximal error was caused by the difficulty in accurately reconstructing the tip of the cone and the pyramid.

	Cone	Pyramid
Maximal Error	0.0215 (7.26%)	0.0228 (6.90%)
Mean Error	0.0056 (1.87%)	0.0043 (1.30%)
Mean Square Error	0.0084 (2.61%)	0.0065 (1.95%)

Table 1: Reconstruction errors averaged over three runs (in meters and percentage of object diameter)

While improvements may be made by precisely calibrating the camera and lighting system, by adding more light sources, and by obtaining a silhouette from the side camera (to eliminate ambiguity about the top of the surface), the system meets its goal of providing virtual presences for physical objects in a quick and timely manner that encourages spontaneous interactions.

8. Putting It to Use: Spontaneous Gesture Interfaces

All the components of the Perceptive Workbench, deictic gesture tracking, object recognition, tracking, and reconstruction, can be combined into a single, consistent framework. The Perceptive Workbench interface detects how the user wants to interact with it and automatically switches to the desired mode.

When the user moves his hand above the display surface, the hand and arm are tracked as described in Section 4. A cursor appears at the projected hand position on the display surface, and a ray emanates along the projected arm axis. These can be used in selection or manipulation, as in Figure 12a. When the user places an object on the surface, the cameras recognize this and identify and track the object. A virtual button also appears on the display (indicated by the arrow in Figure 12b). Through shadow tracking, the system determines when the hand overlaps the button, selecting it. This action causes the system to capture the 3D object shape, as described in Section 5.

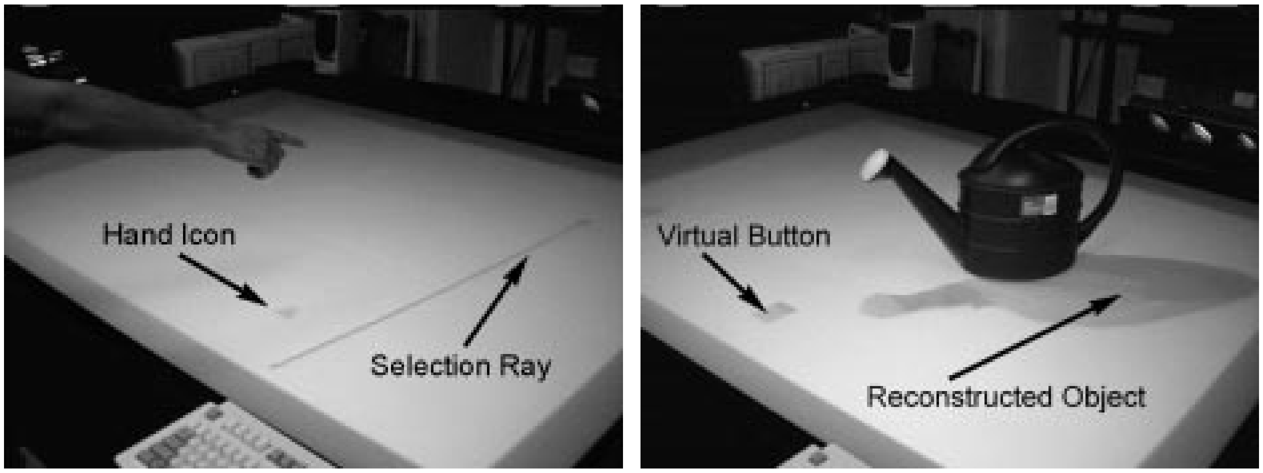


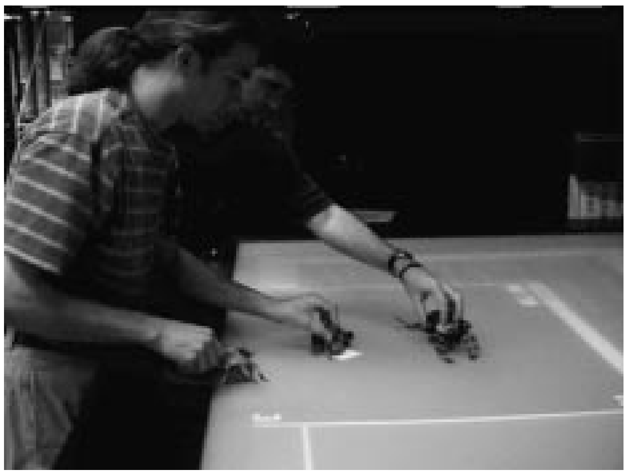
Figure 12: (a) Pointing gesture with hand icon and selection ray; (b) Virtual button rendered on the screen when object is detected on the surface.

The decision whether or not there is an object on the desk surface is made easy by the fact that shadows from the user's arms always touch the image border. Thus, if a shadow is detected that does not touch any border, the system can be sure that it is caused by an object on the desk surface. As a result, it will switch to object recognition and tracking mode. Similarly, the absence of such shadows, for a certain period, indicates that the object has been taken away, and the system can safely switch back to gesture tracking mode. Note that once the system is in object recognition mode, the ceiling lights are switched off, and the light sources underneath the table are activated instead. It is therefore safe for the user to grab and move objects on the desk surface, since his arms will not cast any shadows that could disturb the perceived object contours.

This set provides the elements of a perceptual interface, operating without wires and without restrictions as to objects employed. For example, we have constructed a simple application where objects placed on the desk are selected, reconstructed, and then placed in a "template" set, displayed as slowly rotating objects on the left border of the workbench display. These objects can then be grabbed by the user and could act as new physical icons that are attached by the user to selection or manipulation modes. Or the shapes themselves could be used in model-building or other applications.

An Augmented Reality Game

We have created a more elaborate collaborative interface using the Perceptive Workbench. This involves the workbench communicating with a person in a separate space wearing an augmented reality headset. All interaction is via image-based gesture tracking without attached sensors. The game is patterned after a martial arts fighting game. The user in the augmented reality headset is the player, and one or more people interacting with the workbench are the game masters. The workbench display surface acts as a top-down view of the player's space. The game masters place different objects on the surface, which appear to the player as distinct monsters at different vertical levels in his space. The game masters move the objects around the display surface, toward and away from the player; this motion is replicated in the player's view by the monsters which move in their individual planes. Figure 13a shows the game masters moving objects, and Figure 14b displays the moving monsters in the virtual space.



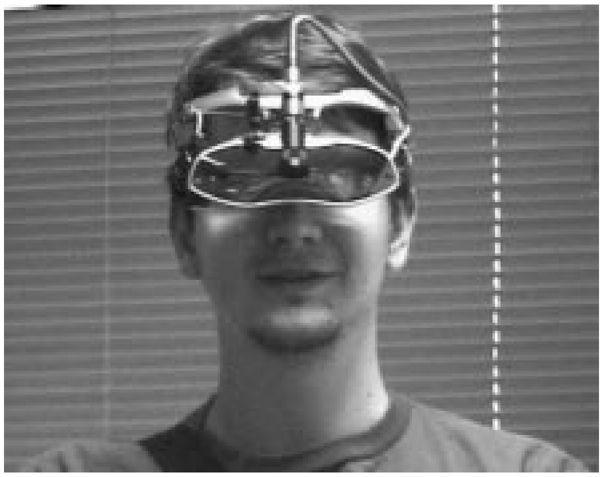


Figure 13: (a) Two game masters controlling virtual monsters; (b) hardware outfit worn by mobile player.

The mobile player wears a "see-through" Sony Glasstron (Figure 13b) equipped with two cameras. Fiducials or natural features in the player's space are tracked by the forward facing camera to recover head orientation. This allows graphics (such as monsters) to be rendered roughly registered with the physical world. The second camera looks down at the player's hands to recognize "martial arts" gestures [Starner98].

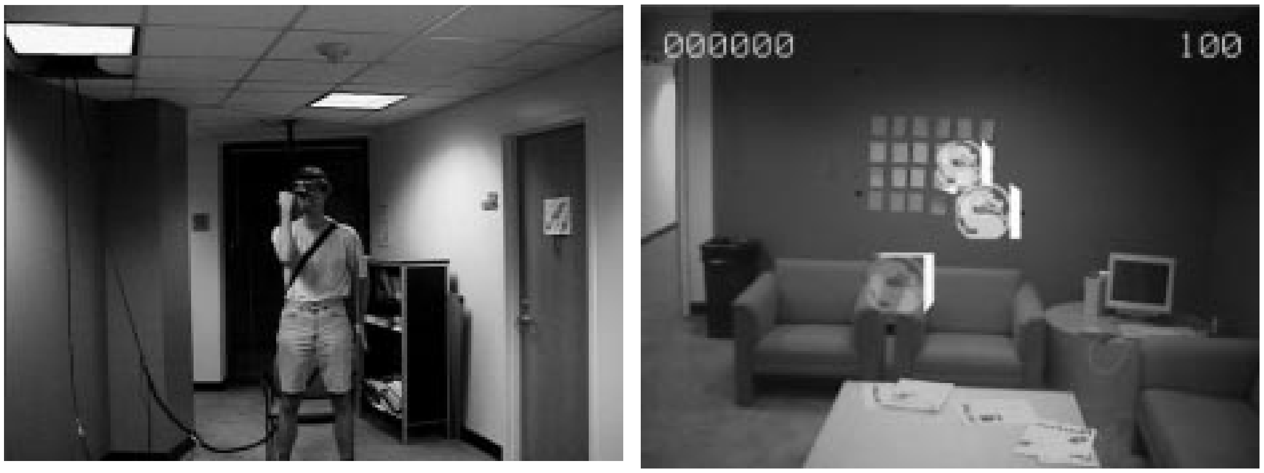


Figure 14: (a) Mobile player performing Kung-Fu gestures to ward off monsters; (b) Virtual monsters overlayed on the real background as seen by the mobile player.

While a more sophisticated hidden Markov model system is under development, a simple template matching method is sufficient for recognizing a small set of martial arts gestures. To effect attacks on the monsters, the user accompanies the appropriate attack gesture (Figure 14a) with a Kung Fu yell ("heee-YAH"). Each foe requires a different gesture. Foes that are not destroyed enter the player's personal space and injure him. Enough injuries will cause the player's defeat.

The system has been used by faculty and graduate students in the GVU lab. They have found the experience compelling and balanced. Since it is difficult for the game master to keep pace with the player, two or more game masters may participate (Figure 13a). The Perceptive Workbench's object tracker scales naturally to handle multiple, simultaneous users. For a more detailed description of this application, see Starner *et al.* [Starner00].

3D Terrain Navigation

We have developed a global terrain navigation system on the virtual workbench which allows one to fly continuously from outer space to terrain or buildings with features at one foot or better resolution [Wartell99]. Since features are displayed stereoscopically, the navigation is both compelling and detailed. In our third person navigation interface, the user interacts with the terrain as if it were an extended relief map laid out below one on a curved surface. Main interactions include zooming, panning, and rotating. Since the user is head-tracked he can move his head to look at the 3D objects from different angles. Previously, interaction has been by using button sticks with six degrees of freedom electromagnetic trackers attached.

We employ the deictic gestures of the Perceptive Workbench, as described in Section 5, to remove this constraint. Direction of navigation is chosen by pointing and can be changed continuously (Figure 15c). Moving the hand towards the display increases speed towards the earth and moving it away increases speed away from the earth. Panning is accomplished by lateral gestures in the direction to be panned (Figure 15a). Rotation is accomplished by making a rotating gesture with the arm (Figure 15b). At present these three modes are chosen by keys on a keyboard attached to the workbench. In the future we expect to use gestures entirely (*e.g.*, pointing will indicate zooming).

Although there are currently some problems with latency and accuracy (both of which will be diminished in the future), a user can successfully employ gestures for navigation. In addition the set of gestures are quite natural to use. Further, we find that the vision system can distinguish hand articulation and orientation quite well. Thus we will be able to attach interactions to hand movements (even without the larger arm movements). At the time of this writing, a hidden Markov model framework has been developed to allow the user to train his own gestures for recognition. This system, in association with the terrain navigation database, should allow more sophisticated interactions in the future.

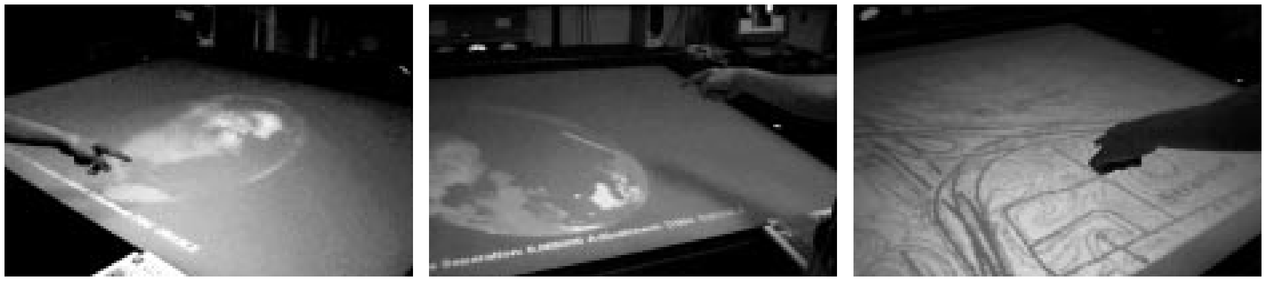


Figure 15: Terrain navigation using deictic gestures: (a) panning; (b) rotation (about an axis perpendicular to and through the end of the rotation lever); (c) zooming in.

Telepresence, CSCW

As another application of the Perceptive Workbench, we have built a small telepresence system. Using the sample interaction framework described at the beginning of this section, a user can point to any location on the desk, reconstruct objects, and move them across the desk surface. Every one of his actions is immediately applied to a virtual reality model of the workbench mirroring the current state of the real desk. Thus, when performing deictic gestures, the current hand and pointing position is displayed on the model workbench by a red selection ray. Similarly, the reconstructed shapes of objects on the desk surface are displayed at the corresponding positions in the model (Figure 16). This makes it possible for co-workers at a distant location to follow the user's actions in real-time, while having complete freedom to choose a favorable view point.

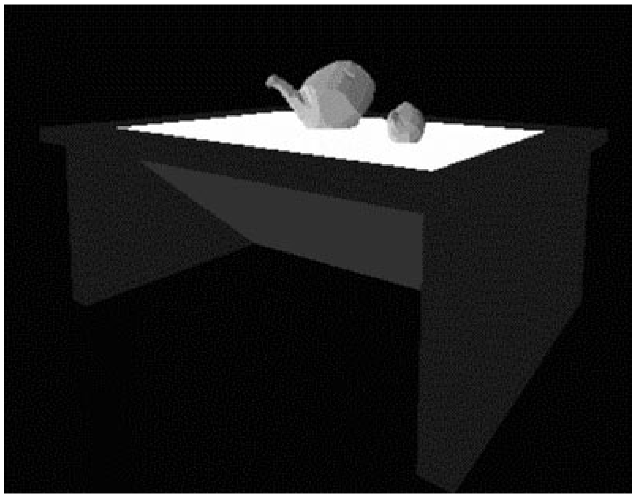


Figure 16: An example for a telepresence system: A virtual instantiation of the workbench mirroring, in real-time, the type and position of objects placed on the real desk.

9. Future Work and Conclusions

Several improvements can be made to the Perceptive Workbench. Higher resolution reconstruction and improved recognition for small objects can be achieved via an active pan/tilt/zoom camera mounted underneath the desk. The color side camera can be used to improve 3D reconstruction and construct texture maps for the digitized object. The reconstruction code can be modified to handle holes in objects and to correct errors caused by non-square pixels. The latency of the gesture/rendering loop can be improved through code refinement and the application of Kalman filters. With a difficult object, recognition from the reflections from the light source underneath can be successively improved by using cast shadows from the light sources above or the 3D reconstructed model directly. Hidden Markov models can be employed to recognize symbolic hand gestures [Starner98] for controlling the interface. Finally, as hinted by the multiple game masters in the gaming application, several users may be supported through careful, active allocation of resources.

In conclusion, the Perceptive Workbench uses a vision-based system to enable a rich set of interactions, including hand and arm gestures, object recognition and tracking, and 3D reconstruction of objects placed on its surface. These elements are combined seamlessly into the same interface and can be used in various applications. In addition, the sensing system is relatively inexpensive, retailing approximately $1000 for the cameras and lighting equipment plus the cost of a computer with one or two video digitizers, depending on the functions desired. As seen from the multiplayer gaming and terrain navigation applications, the Perceptive Workbench provides an untethered and spontaneous interface that encourages the inclusion of physical objects in the virtual environment.

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