PROJECTOR-CAMERA SYSTEMS FOR IMMERSIVE TRAINING

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ABSTRACT

Real time computer graphics are limited in that they can only be displayed on projection screens and monitors. Monitors and projection screens cannot be used in live fire training or scenarios in which the displays could be physically damaged by trainees. To address this issue, we have developed projection systems using computer vision based color correction and image processing to project onto non-ideal surfaces such as painted walls, cinder blocks, and concrete floors. These projector-camera systems effectively paint the real world with digital light. Any surface can become an interactive projection screen allowing unprepared spaces to be transformed into an immersive environment. Virtual bullet holes, charring, and cracks can be added to real doors, walls, tables, chairs, cabinets, and windows. Distortion correction algorithms allow positioning of projection devices out of the field of view of trainees and their weapons. This paper describes our motivation and approach for implementing projector-camera systems for use within the FlatWorld wide area mixed reality system.

1. INTRODUCTION

Projection technology is widely used for immersive virtual reality applications. In comparison to head mounted displays, projection systems facilitate free movement of participants and can be tightly integrated with the physical environment.

1.1. Rear projection immersive virtual reality

There are two basic approaches used for projection based virtual reality: projection from behind the screen and projection from the front. An example of the latter is the “Being There” project [Low et al., 2001] at the University of North Carolina at Chapel Hill. In this system, walls of white styrofoam blocks are arranged to reproduce the basic layout of a room. Imagery is front projected onto the styrofoam blocks making these surfaces appear as textured walls with virtual windows and doors.

Front-projection systems are compact, but there are drawbacks: shadows caused by people walking in front of projectors and difficulties preserving light polarization needed for passive stereoscopic display.

Most rear projection based virtual reality systems are derived from the CAVE [Cruz-Neira, Sandin and DeFanti, 1993]. The CAVE is a rear projected cube, where 3 to 6 sides are screens, creating a highly immersive virtual environment.

The FlatWorld project at the University of Southern California Institute for Creative Technologies [Pair et al., 2003 and Treskunov, Pair and Swartout, 2004] creates a mixed reality environment, combining stereoscopic rear-projection with physical props tightly integrating virtual and real scene elements.

Real scene elements such as walls and furniture introduced by the Flatworld concept could be further enhanced by incorporating front-projection technology. For example, the Shader Lamp system (Raskar et al, 2001) suggests that projecting onto color neutral real objects can reproduce different “appearances, including alternate shading, lighting, and even animation.”

Our prototype projector-camera system described later in the paper, utilizes front-projection for simulating bullet damage on a real wall.

1.2. Limitations of front projection technology

As mentioned previously, two drawbacks of front projection are shadows and the loss of light polarization. In FlatWorld, we can alleviate the shadow problem either by placing projectors and props such that users do not intersect projection beams or by using multiple projectors. The loss of stereo polarization is not critically important since we plan to use front projection for simulating damage effects that appear realistic even though the imagery is not stereoscopic. Our approach is challenging in that we plan to project onto unprepared, arbitrary surfaces as opposed to specialized screens or neutral surfaces as in the “Being There” or “Shader Lamp” approaches.

By avoiding the shadow and polarization issues, new problems are introduced in our system. We placed the video projector in an out-of-sight location at an oblique angle which creates geometric distortion in the projected image. Furthermore, using regular objects such as walls and tables as projection targets is problematic since they do not have the properties of ideal flat, white matte screens.

Consequently, there is a need for a geometry and radiometric compensation step before projecting. Fortunately, the computer vision research and development community provides answers we can employ.

2. RELATED COMPUTER VISION WORK

Ramesh Raskar proposed a rendering technique to display perceptively correct images when a projector is oblique with respect to a planar display surface [Raskar, 1999 and Raskar, 2000]. His proposed method can be integrated into a graphics engine, incurring no additional cost during real-time rendering. If the surface is not planar, two pass rendering may be employed [Raskar et al, 1998]. During the first pass the "desired image is stored as a texture map. In the second pass the texture is effectively projected from the user's viewpoint onto the polygonal model of the display surface."

The CAVE Lab at Columbia University developed an algorithm for color correction when projecting onto lambertian colored surfaces without inter-reflections [Nayar et al., 2003 and Grossberg et al., 2004]. In later work [Fujii, Grossberg and Nayar, 2005], they adapted the method to dynamically handle changing lighting conditions to a certain extent.

Modern projectors have limited dynamic range. As a result, applying global color compensation techniques creates clipping problems and low contrast images. Work has been conducted to overcome this problem by exploiting human visual perception properties for several projectors [Majumder and Stevens, 2005] and for dynamic display conditions [Grundhfer and Bimber, 2006].

In practical situations, complex lighting effects need to be taken into account. The augmented reality group at Bauhaus University recently proposed [Bimber et al., 2006] a method for compensating for indirect scattering in real-time using reverse radiosity. Such scattering compensation is essential when projection screens are concavely shaped.

More complex effects need to be addressed in situations in which subsurface scattering is important such as projecting onto marble. The full interaction between the projected and observed image is described by the light transport matrix. An efficient method for capturing this matrix has been proposed by a recent paper from the Stanford Computer Graphics Lab [Sen et al., 2005]. To apply light transport based compensation, one needs to either solve a system of linear equations or apply the pseudo-inverse of the light transport matrix in real-time as has been done by [Wetzstein and Bimber, 2006] using a graphics card's GPU. This technique is the most general approach for a single projector case.

It is also possible to use multiple projectors to increase depth of field [Bimber and Emmerling, 2006(2)] or to eliminate shadows [Cham et al., 2003].

3. FLATWORLD INTEGRATION

In early 2006 we began prototyping the use of front-projection and projector-camera systems in the FlatWorld wide area mixed reality environment. Our initial demonstration aimed to simulate AK-47 bullet impacts on an unprepared real wall of the FlatWorld environment. The bullets would be fired by a virtual stereoscopic rear-projected insurgent firing into the room (see Fig. 1). To avoid shadows from participants, we planned to place a projector above the ceiling at a sharp angle with respect to the wall projection target (see Fig. 2). Computer vision based geometry correction would be used to compensate for the non ideal projector alignment.

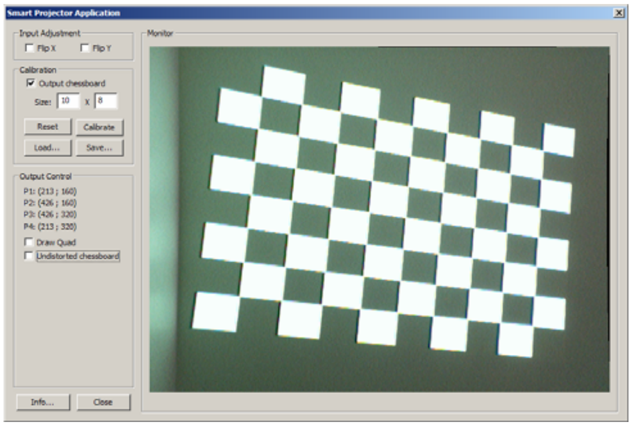
Fig. 1: Conceptual rendering of a virtual insurgent firing virtual bullet holes into a real wall.

Fig. 2: Projector placed above the ceiling.

3.1. Calibration and integration with rendering pipeline

Our geometry compensation technique is based on Ramesh Raskar's work [Raskar, 1999 and Raskar, 2000].

In our approach, the system is calibrated by projecting a chessboard pattern and photographing it with a camera placed in an ideal projector position in front of the projected area (Fig. 3). During this stage, we decrease noise by applying a temporal average to a sequence of 100 captured distortion corrected images. The OpenCV library [OpenCV] was used for camera calibration. To correct for distortion, chessboard corners are extracted with sub-pixel accuracy and a 3x3 homography matrix H is calculated which transforms normalized 2D coordinates of the captured chessboard corners into projected corners. Corner coordinates are normalized to be in the [-1; +1] range to eliminate the different spatial resolutions of the projector and camera.



☐ Flip X ☐ Flip Y

☑ Output chessboard

Size: 10 x 8

P1: (213 ; 160)
P2: (426 ; 160)
P3: (426 ; 320)
P4: (213 ; 320)

☐ Draw Quad
☐ Undistorted chessboard

Fig. 3: Calibration pattern

The matrix H was loaded during the initialization of the rendering application [Treskunov, Pair, and Swartout, 2004]. It was transposed to take into account different matrix conventions between OpenCV and DirectX. Next, the 4x4 projection matrix A was constructed as in [Raskar, 1999 and Raskar, 2000].

$$A = \begin{bmatrix} h_{11} & h_{21} & 0 & h_{31} \\ h_{12} & h_{22} & 0 & h_{32} \\ 0 & 0 & 1 - |h_{31}| - |h_{32}| & 0 \\ h_{13} & h_{23} & 0 & 1 \end{bmatrix}$$

Inside the rendering setup call, the projection matrix P was calculated as usual given camera and viewport information. It was then modified by the stored matrix A.

$$P' = P * A$$

Here, multiplication order is reversed to take into account transposition. The p'_{34} element was reset to equal 1 after multiplication for the matrix to be “W-friendly”.

After this setup process, the rendering loop runs without additional overhead.

3.2. The advantages of physical props

As mentioned earlier, the use of physical props in the FlatWorld system avoids many of the challenges that exist in rear projection systems like the CAVE. For example, a vertical column placed at the corner of two screens masks rendering latency between two projection channels. Rubble placed on the floor blocks a user access to areas where rendering artifacts appear when a tracked user is too close to the screen. The elements are placed in such a way that they do not harm the overall user experience.

In a similar fashion we resolved the problems introduced by DLP projector black levels. Because DLP projectors cannot project pure black, the projected area is clearly visible and appears artificial. To alleviate this problem, we strategically placed a spot light to mask the boundary of the projected area.

3.3. Initial demonstration

Our prototype scenario, completed in August 2006, is seen in Figure 4 and Figure 5. After a virtual insurgent fires rounds into the room, a damage animation is displayed on the opposite wall, creating highly convincing damage effects.

Fig. 4: Virtual insurgent firing toward a real wall in the FlatWorld one room prototype.

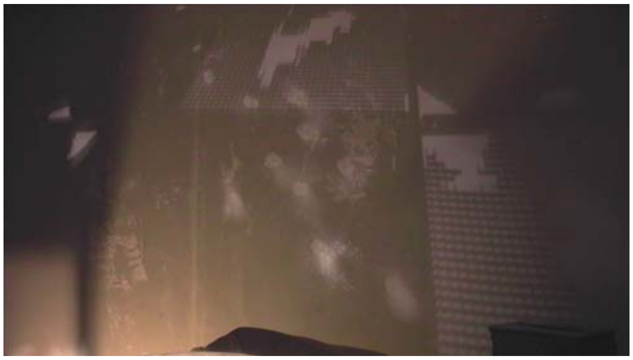


Fig. 5: Realistic computer generated bullet holes and debris appear on the opposite real wall.

CONCLUSIONS

Our ongoing projector-camera system research and development work will allow us to transform any solid surface into a projection screen. This capability allows a virtual insurgent presented on a digital flat to be able to fire a weapon and destroy a real wall in the room. An angry virtual civilian could throw virtual rocks that crack real tables and chairs. Our work also facilitates virtual humans capable of casting projector generated shadows into the real world. Training scenarios utilizing our work will be more stressful and convincing, better preparing the soldier for similar situations on the real battlefield.

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