PROJECTOR-BASED THREE DIMENSIONAL GRAPHICS

by

Ramesh Raskar

A dissertation submitted to the faculty of the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Computer Science.

Chapel Hill

2002

Approved by:

Co-Advisor: Henry Fuchs

Co-Advisor: Gregory Welch

Reader: Guido Gerig

Gary Bishop

Leonard McMillan

ABSTRACT

Ramesh Raskar

Projector-based Three Dimensional Graphics

(Under the direction of Henry Fuchs and Gregory Welch)

Light projectors can be arranged into electronic displays that offer large, bright, and high resolution images. However, despite their unique characteristics, projectors have been treated like any other two-dimensional display devices, e.g. CRT monitors or LCD panels, to create flat and usually rectangular images. Even the growth of three dimensional computer graphics has followed this limitation.

To improve and widen the range of applications of projectors, in this dissertation I present a single unified geometric framework for projector-based graphics. It is based on the notion of the projector as the dual of a camera. The geometric framework is based on (i) the analytical projection model, (ii) the geometric representation of the display surface and (iii) the viewer location. The framework can be used for practically all the projector-based applications. For classic projector-based systems, such as tiled displays or immersive panoramic displays, the framework provides a fundamentally different approach that allows greater freedom and flexibility. In addition, it enables a new class of projector-based visualization methods.

ACKNOWLEDGMENTS

Thanks to

My co-advisors Henry Fuchs and Greg Welch for their guidance and encouragement, for introducing me to many of the topics in this dissertation, and for their support and patience through a difficult year after my thesis defense

My committee members Gary Bishop, Guido Gerig and Leonard McMillan for many wonderful discussions and suggestions

Herman Towles and The UNC STC group for providing an excellent research environment

Mike Brown, Matt Cutts and Kok-lim Low who worked closely with me to build many research prototypes

Gopi M., for his friendship, and for many stimulating conversations

John 'Spike' Hughes (Brown U.), Brent Seales (U. of Kentucky) and Peter Schroeder (CalTech) for excellent suggestions

DARPA, NSF, NTII, Link Foundation and Intel for funding my research

Linda Welch, George Spindler and Marty Spindler for the wooden Taj Mahal model used in Shader Lamps demonstration

Andrei State for his beautiful sketches

Joe Marks (MERL-Research Director) for giving me the freedom to complete the dissertation at MERL

Many fellow grad students with whom I spent so much time, especially Deepak Bandyopadhyay Sumedh Barde, Wei-Chao Chen, Gentaro Hirota, Adam Lake, Shankar Krishnan, Aditi Majumder, Ajit Mascarhenas, Atsuko Negishi, Amol Pattekar, Voicu Popescu, Sunay Tripathi, Ruigang Yang, and many others

The staff of the UNC computer science department, for helping me in innumerable ways and for being a pleasure to work with

My parents for their love and for being supportive of whatever I wanted to do in life, my brother Prakash for his motivating spirit and guidance, my sister Nanda for her selfless dedication and her emphasis on education, my sister Neeta for her humor and good cheer, and Rebecca for all she is.

CHAPTER 1

Introduction

Light projectors as a display medium present unique benefits and challenges. They have long been used to create rich and vivid images for presentations or to project movies for large audiences with moving images and brilliant colors for entertainment. Thanks to the rapidly decreasing size and cost, projectors are now increasingly being used for interactive computer graphics applications.

The research presented in this dissertation addresses the issues and opportunities in using three-dimensional computer graphics techniques for projector-based displays. I describe a generalized approach for projector-based three dimensional graphics. The approach allows one to re-formulate the classic problems previously solved with disparate solutions. In addition, the generalized approach enables a new class of graphics applications.

In this chapter, I first discuss the motivation for treating projector-based 3D graphics separate from conventional 3D graphics. Then I introduce an enhanced geometric framework that provides a basis for dealing with all projector-based rendering and calibration problems. Finally, I present the outline for rest of this dissertation.

1.1 The Problem and Approach

Traditionally, a light projector is treated like any other two-dimensional display device such as a CRT or a LCD screen to create flat and, usually, rectangular images. Note, however, that a light projector can be treated as the dual of a camera, i.e. a projection device relating 3D space and an image. For a camera, an analytical camera model such as the thin lens model or the pinhole projection model, is a valuable abstraction that is used in various areas of computer vision, e.g. projective geometry and calibration [Brown71, Newman73, LH81, Faugeras93]. In image-based rendering, the chosen camera

Traditionally, projectors are employed in a restrictive manner to achieve rectilinear projections and do not exploit the flexibility provided. However, it is obvious that we can use projectors and display surfaces in many different geometric configurations. We need not restrict ourselves to planar screens. The freedom in size, combination and shape allows us to display animated, high-resolution and bright images in a range of projector systems, from wide-field-of-view displays to set ups in which physical objects are illuminated from many directions by surrounding projectors.

It is also worthwhile to note that projector based systems have the following geometric limitations.

(i) The limited depth of field, i.e. the range of depth over which a projected image remains in focus, poses a challenge to projecting on oblique or non-planar surfaces.

(ii) The perceived image intensity is dependent on relative orientation, distance and reflectance properties of the display surface.

(iii) In front-projection systems, shadows can affect the displayed imagery.

Projectors which use a 3-lens system for red, green and blue color channels, are especially difficult to use on a non-planar surface. They pose the challenge of converging the three colors on the display surface. However, newer single lens projectors with relatively small aperture size have a large usable range of depth. I will revisit the issue of depth of field and its relationship with aperture size, later in the appendix. We can also look forward to projectors with more coherent light sources based on lasers (e.g. [Colorvision] which uses RGB lasers rather than arc lamps allowing a large depth of field) or systems with innovative optics, e.g. Elumens' display domes [Elumens]. I discuss the effect of display surface orientation, reflectance and static shadows due to self-occlusion in a later chapter. There has been some recent work in eliminating human shadows by using redundant illumination, but dynamic occlusion remains a difficult problem.

Despite the limitations, a projective display device remains the first choice for creating large images. At least in a limited way, the advantages of size and combination have been used by others, e.g. to blend overlapping projectors for seamless planar (or near-planar) displays. In this thesis I show that, if we choose to use the analytical model, these advantages can be exploited to a great extent with new 3D computer graphics and computer vision algorithms. The algorithms include camera-based calibration methods as well as new rendering, warping and blending techniques to display images of 3D scenes for a tracked moving user.

this stage, Prof. Greg Welch formulated the important idea of unification of capture and display. Specifically, he realized that if we had the dynamic image-based model of the display surface, we can also correct for changes in the time-varying geometric characteristics of the illuminated surfaces. The geometric characteristics themselves can be recovered by observing the illuminated surfaces with cameras.

The idea of integrating capture and display with projectors and cameras can be applied to a more common case, where both, display surfaces and projectors, are static. The outcome was the camera-based registration technique, which I formalized for generalized immersive panoramic systems [Raskar99a]. It worked beautifully when applied to overlapping multi-projector spatially immersive display (SID). The problem of mis-registration of images with physical surfaces led us to the realization that this is essentially an augmented reality problem, leading to further exploration in projector-based spatially augmented reality. An evening at a clay-modelling studio was responsible for ideas for Shader Lamps [Raskar01c]. I explored this relationship – between projectors and the three-dimensional surfaces they illuminate – in multiple ways and in different configurations. As it turns out, the main task of rendering computer graphics images for all these variations can be specified using a single conceptual framework.

1.7 Summary

Projector-based display systems are becoming popular because they offer the attractive combination of a great number of pixels over a large area with a wide range of possible geometric configurations. However, projectors are currently restricted in their applications. They can be used for far more than just large format displays. In this chapter, I introduced the notion of a projector as a versatile projection device and its analytic projection model as the main component of a general framework. In this thesis, I discuss the geometric issues involved in using projectors for displaying images rendered with 3D computer graphics methods. In the next chapter I describe the relevant previous work in computer graphics and projector-based systems.

CHAPTER 2

Background

This chapter reviews the background and some earlier work related to this dissertation. I first describe the basic types of projector based systems and the techniques used. Then, I compare my image-based illumination techniques with the image-based rendering (IBR) techniques that use multiple images captured with a camera. Since I am exploiting the notion of a projector as the dual of a camera, there is a significant overlap between this thesis and the work in IBR. Previous work related to specific topics is discussed in the corresponding chapters later in this thesis.

2.1 Projector-based environments

Projectors were primarily used for movies, flight simulators and in amusement parks - in large or expensive installations. However, thanks to the size and cost factors, in the last few years projectors are being used in university labs [Cruz93, Humphreys99, Li00], small entertainment installations [Bennett00] and even in offices [Raskar98b, Bishop00, Welch00].

In this dissertation, I focus primarily on immersive projector-based systems that display perspectively correct images of 3D virtual scenes. Under a very simple and restricted geometric configuration, the idealized representation of the immersive display problem can be stated quite directly. However, the implementation of a real system faces the practical issues of deviation from the design, imprecise geometry, aliasing, blending and many sources of mis-registration. There are a variety of ways to cope with these issues, and as described below many large format or panoramic displays with and without user head-tracking have been developed.

fortune teller “Madame Leota” inside a real crystal ball [Liljegren90]. On a more physically grand scale, projectors have recently been used to render a variety of lighting and projected imagery on a very large architectural scale. For example, in 1952 Paul Robert-Houdin used sounds and colored lights on a building for nighttime entertainment. The most well-known modern realization of this idea is the Son et Lumiere (light show) at/on the Blois castle in the Loire Valley (France) (Figure 2.3). I consider this process as a subset of ’image-based illumination’ techniques I cover later in this dissertation. In Chapter 5, I describe the other systems and techniques for illumination of objects in more detail. I also provide a comprehensive analysis with new results.

2.2 Image-based rendering

Image-based rendering techniques rely on pixel reprojection from source images onto the target image in order to produce a novel virtual view. In [Kang97], the author has identified four distinct (but not necessarily mutually exclusive) categories of image-based rendering techniques . These categories are created based primarily on the nature of the scheme for pixel indexing or transfer. They are: non-physically based image mapping, mosaicing, interpolation from dense samples, and geometrically-valid pixel reprojection.

Image mapping examples are morphing and 2D image warping. Several image warping techniques and examples of morphing are given in Wolberg’s book [Wolberg92]. An example of a warping technique is the 2-D spline mesh mapping. In this technique, the user specifies separate grids of points in both the source and target images. Each target grid point has a corresponding source grid point. Displacements between grid points can be computed using some form of interpolation; linear interpolation is the easiest and hence most popular. I use the image warping techniques to pre-distort images before projection. The warping operation is performed efficiently using the traditional texture mapping graphics hardware.

The idea behind interpolation from dense samples is to create an enormous lookup table by taking many image samples from different viewpoints. Then, the image associated with any given arbitrary viewpoint is synthesized by interpolating the stored lookup table. Two popular approaches are light field rendering [Levoy96], and the lumigraph [Gortler96].

Below I describe the influence of the other two categories, mosaicing and pixel reprojection, on the image synthesis techniques I describe later in this thesis. I also discuss a problem closely

3.5 Summary

In this chapter I introduced the general geometric framework for projector-based graphics and described the related rendering framework and calibration goals. In the next three chapters, I describe the applications of the framework to form a concrete basis for explanation and analysis.