Theory and Methods of Lightfield Photography

SIGGRAPH 2009

Todor Georgiev
Adobe Systems
tgeorgie@adobe.com

Andrew Lumsdaine
Indiana University
lums@cs.indiana.edu

Web Page

http://www.tgeorgiev.net/Asia2009/

Course Description

Computational photography is based on capturing and processing discrete representations of all the light rays in the 3D space of a scene. Compared to conventional photography, which captures 2D images, computational photography captures the entire 4D "lightfield," i.e., the full 4D radiance. To multiplex the 4D radiance onto conventional 2D sensors, light-field photography demands sophisticated optics and imaging technology. At the same time, 2D image creation is based on creating 2D projections of the 4D radiance.

This course presents light-field analysis in a rigorous, yet accessible, mathematical way, which often leads to surprisingly direct solutions. The mathematical foundations will be used to develop computational methods for lightfield processing and image rendering, including digital refocusing and perspective viewing. While emphasizing theoretical understanding, we also explain approaches and engineering solutions to practical problems in computational photography.

As part of the course, we will demonstrate a number of working light-field cameras that implement different methods for radiance capture, including the microlens approach of Lippmann and the plenoptic camera; the focused plenoptic camera, the Adobe lens-prism camera; and a new camera using a "mosquito net" mask. Various computational techniques for processing captured light-fields will also be demonstrated, including the focused plenoptic camera and real-time radiance rendering.

Prerequisites

This course is intended for anyone interested in learning about lightfield photography. The prerequisites are a basic understanding of ray optics. The course is of intermediate difficulty.

Course Syllabus

Background and Motivation

We open the course by discussing some of the fundamental limitations with conventional photography and present some motivating examples of how lightfield photography (radiance photography) can overcome these limitations.

Radiance Theory and Modeling

The theory and practice of radiance photography requires a precise mathematical model of the radiance function and of the basic transformations that can be applied to it.

Ray Transforms

We begin the theoretical portion of the course by presenting basic ray optics and ray transformations, cast in the language of matrix operations in phase space. This portion of the tutorial will cover:

- Position / Direction parameterization

- Transport through space
- Lens transformation
- Transformations in phase space
- Composition of Optical Elements
- Principle Planes

Radiance

With the machinery of ray transforms in hand, we can characterize how optical elements will transform radiance.

- Mathematical properties of radiance
- Conservation of volume
- Conservation of radiance
- Transformation by optical elements
- Image rendering

Capturing Radiance with Radiance Cameras

Although radiance is a 4-dimensional quantity, to capture it, we still must use 2-dimensional sensors. In this portion of the tutorial we discuss how cameras can be constructed to multiplex 4-dimensional radiance data as a 2-dimensional image. Beginning with basic camera models, we will develop and analyze

- Pinhole camera
- "2F" camera
- Traditional 2D camera
- Ives' camera
- Lippmann's camera
- Camera arrays

Radiance in the Frequency Domain

Analyzing radiance in the frequency domain provides some interesting new insights into radiance cameras as well as some surprising new types of cameras. In this portion of the course, we will discuss

- Fourier transform of radiance
- Fourier transform of radiance transforms
- Cameras of Ives and Lippmann
- MERL heterodying cameras

The Focused Plenoptic Camera

Recently, a new type of plenoptic camera has been developed that provides significantly improved spatial resolution when compared to the traditional approach. In this portion of the course, we develop an analyze the focused plenoptic camera (Plenoptic 2.0), focusing on the following topics:

- Adelson's plenoptic camera
- Focused plenoptic camera
- Comparison and contract of the two plenoptic camera approaches
- Comparison of the microimages
- Sampling in phase space

Hands-On with Radiance Cameras

A number of different working radiance cameras will be demonstrated and different particular approaches to radiance capture will be highlighted. Tutorial participants will have hands-on with the following radiance cameras:

- Microlens approach of Lippmann (showing working microlens arrays)
- Plenoptic camera (demonstrating plenoptic camera in action)
- MERL mask enhanced cameras (showing masks and coding approaches)
- Adobe lens-prism camera (showing the lenses)
- "Mosquito net" mask camera

Computational Methods for Radiance

Radiance photography has been made practical by the availability of computational techniques that can perform 2D image rendering from the 4D radiance function. The following computational issues will be discussed during this portion of the tutorial:

- Sensors, pixels, digital image representations
- Image rendering
- Space multiplexing
- Frequency multiplexing ("heterodyning")
- Fourier-slice refocusing
- Methods for Plenoptic 2.0
- Efficient (real-time) implementation using GPU Hardware

Timeline

- 9:00-9:10 Background and Motivation
- 9:10-10:40 Radiance Theory and Modeling
  - 9:10-9:35 Ray Transforms
  - 9:35-9:50 Radiance
  - 9:50-10:05 Capturing Radiance with Cameras
  - 10:05-10:40 The Focused Plenoptic Camera
- 10:40-10:45 Hardware Demonstration
- 10:45-11:00 Break (Optional: Hands On with Radiance Cameras)
- 11:00-11:15 Radiance Theory and Modeling (Continued)
  - 11:00-11:15 Radiance in the Frequency Domain
- 11:15-12:45 Computational Methods for Radiance
  - 11:15-11:45 Methods for Plenoptic 1.0
  - 11:45-12:00 Fourier Slice Refocusing
  - 12:00-12:20 Methods for Plenoptic 2.0
  - 12:20-12:40 Efficient Implementation with GPU Hardware
- 12:40-12:45 Wrap Up

About the Presenters

Todor Georgiev is a researcher at Adobe Systems, working closely with the Photoshop group. Having extensive background in theoretical physics, he concentrates on applications of mathematical methods taken from physics to image processing, graphics, and vision. He is the author of the Healing Brush tool in Photoshop (2002), the method better known as Poisson image editing. He has published several articles on applications of the mathematics of covariant derivatives in image processing and vision. He is working on a wide range of theoretical and practical ideas in optics, light field cameras and capture/manipulations of the optical field. His recent work concentrates on radiance camera designs. He has a number of papers and patents in these and related areas.

Andrew Lumsdaine received the PhD degree in electrical engineering and computer science from the Massachusetts Institute of Technology in 1992. He is presently a professor of computer science at Indiana University, where he is also the director of the Open Systems Laboratory. His research interests include computational science and engineering, parallel and distributed computing, mathematical software, numerical analysis, and radiance photography. He is a member of the IEEE, the IEEE Computer Society, the ACM, and SIAM.