Light field photography and videography

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List of projects

- high performance imaging using large camera arrays
- light field photography using a handheld plenoptic camera
- dual photography
High performance imaging using large camera arrays

Bennett Wilburn, Neel Joshi, Vaibhav Vaish, Eino-Ville Talvala, Emilio Antunez, Adam Barth, Andrew Adams, Mark Horowitz, Marc Levoy

(Proc. SIGGRAPH 2005)
Stanford multi-camera array

- 640 × 480 pixels × 30 fps × 128 cameras
- synchronized timing
- continuous streaming
- flexible arrangement
Ways to use large camera arrays

- widely spaced → light field capture
- tightly packed → high-performance imaging
- intermediate spacing → synthetic aperture photography
Intermediate camera spacing: synthetic aperture photography
Example using 45 cameras
[Vaish CVPR 2004]
Tiled camera array

Can we match the image quality of a cinema camera?

• world’s largest video camera
• no parallax for distant objects
• poor lenses limit image quality
• seamless mosaicing isn’t hard
Tiled panoramic image
(before geometric or color calibration)
Tiled panoramic image
(after calibration and blending)
Tiled camera array

Can we match the image quality of a cinema camera?

- world’s largest video camera
- no parallax for distant objects
- poor lenses limit image quality
- seamless mosaicing isn’t hard
- per-camera exposure metering
- HDR within and between tiles
same exposure in all cameras

individually metered

checkerboard of exposures
High-performance photography as multi-dimensional sampling

- spatial resolution
- field of view
- frame rate
- dynamic range
- bits of precision
- depth of field
- focus setting
- color sensitivity
Spacetime aperture shaping

- shorten exposure time to freeze motion → dark
- stretch contrast to restore level → noisy
- increase (synthetic) aperture to capture more light → decreases depth of field
• center of aperture: few cameras, long exposure → high depth of field, low noise, but action is blurred

• periphery of aperture: many cameras, short exposure → freezes action, low noise, but low depth of field
Light field photography using a handheld plenoptic camera

Ren Ng, Marc Levoy, Mathieu Brédif, Gene Duval, Mark Horowitz and Pat Hanrahan

(Proc. SIGGRAPH 2005 and TR 2005-02)
Conventional versus light field camera
Conventional versus light field camera

Subject

Main lens

Photosensor

uv-plane

st-plane

Main lens
Conventional versus light field camera

Subject → Main lens → Photosensor

st-plane

Subject → Main lens

uv-plane
Prototype camera

Contax medium format camera

Kodak 16-megapixel sensor

Adaptive Optics microlens array

125µ square-sided microlenses

\[4000 \times 4000 \text{ pixels} \div 292 \times 292 \text{ lenses} = 14 \times 14 \text{ pixels per lens}\]
Mechanical design

- microlenses float 500µ above sensor
- focused using 3 precision screws
Prior work

• integral photography
  – microlens array + film
  – application is autostereoscopic effect

• [Adelson 1992]
  – proposed this camera
  – built an optical bench prototype using relay lenses
  – application was stereo vision, not photography
Digitally stopping-down

• stopping down = summing only the central portion of each microlens
Digital refocusing

- refocusing = summing windows extracted from several microlenses
A digital refocusing theorem

- an $f/N$ light field camera, with $P \times P$ pixels under each microlens, can produce views as sharp as an $f/(N \times P)$ conventional camera.

- or -

- it can produce views with a shallow depth of field ($f/N$) focused anywhere within the depth of field of an $f/(N \times P)$ camera.
Example of digital refocusing
Refocusing portraits
Action photography

Focusing through a splash of water
Extending the depth of field

- Conventional photograph, main lens at $f/4$
- Conventional photograph, main lens at $f/22$
- Light field, main lens at $f/4$, after all-focus algorithm [Agarwala 2004]
Macrophotography
Digitally moving the observer

- moving the observer = moving the window we extract from the microlenses
Example of moving the observer
Moving backward and forward
Implications

- cuts the unwanted link between exposure (due to the aperture) and depth of field
- trades off (excess) spatial resolution for ability to refocus and adjust the perspective
- sensor pixels should be made even smaller, subject to the diffraction limit
  
  \[36\text{mm} \times 24\text{mm} \div 2.5\mu\text{pixels} = 266 \text{ megapixels}\]
  
  \[20K \times 13K \text{ pixels}\]
  
  \[4000 \times 2666 \text{ pixels} \times 20 \times 20 \text{ rays per pixel}\]
Can we build a light field microscope?

- ability to photograph moving specimens
- digital refocusing → focal stack → deconvolution microscopy → volume data
Dual Photography

Pradeep Sen, Billy Chen, Gaurav Garg, Steve Marschner, Mark Horowitz, Marc Levoy, Hendrik Lensch

(Proc. SIGGRAPH 2005)
Helmholtz reciprocity
Helmholtz reciprocity
Measuring transport along a set of paths

projector

photocell

scene
Reversing the paths

camera

point light

scene
Forming a dual photograph

“dual” camera

“dual” projector

“dual” light

photocell

scene
Forming a dual photograph

“dual” camera

“dual” light

image of scene

scene
Physical demonstration

- light replaced with projector
- camera replaced with photocell
- projector scanned across the scene

conventional photograph, with light coming from right

dual photograph, as seen from projector’s position and as illuminated from photocell’s position
Related imaging methods

• time-of-flight scanner
  – if they return reflectance as well as range
  – but their light source and sensor are typically coaxial

• scanning electron microscope

Velcro® at 35x magnification, Museum of Science, Boston
The 4D transport matrix

projector

photocell

scene
The 4D transport matrix

- Projector: $P$ (pq x 1)
- Camera: $C$ (mn x 1)
- Scene: $T$ (mn x pq)
The 4D transport matrix

\[
C = \begin{bmatrix}
  \text{mn x 1}
\end{bmatrix}
\begin{bmatrix}
  \text{mn x pq}
\end{bmatrix}
\begin{bmatrix}
  \text{pq x 1}
\end{bmatrix}
\]
The 4D transport matrix

\[ C = \begin{bmatrix} \text{mn x 1} \\ \text{mn x pq} \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} \text{pq x 1} \end{bmatrix} \]
The 4D transport matrix

\[ C = \begin{bmatrix} \text{mn x pq} \\ \text{mn x 1} \end{bmatrix} \begin{bmatrix} \text{pq x 1} \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \]
The 4D transport matrix

\[
C = \begin{pmatrix}
0 & 0 \\
1 & 0 \\
\end{pmatrix}
\]
The 4D transport matrix

\[
\begin{bmatrix}
C \\
mn \times 1
\end{bmatrix} =
\begin{bmatrix}
T \\
mn \times pq
\end{bmatrix}
\begin{bmatrix}
P \\
pq \times 1
\end{bmatrix}
\]
The 4D transport matrix

\[
C = \begin{bmatrix}
\text{mn x pq}
\end{bmatrix}
\begin{bmatrix}
\text{mn x 1}
\end{bmatrix}
\begin{bmatrix}
\text{pq x 1}
\end{bmatrix}
\]

applying Helmholtz reciprocity...

\[
C' = \begin{bmatrix}
\text{pq x mn}
\end{bmatrix}
\begin{bmatrix}
\text{pq x 1}
\end{bmatrix}
\begin{bmatrix}
\text{mn x 1}
\end{bmatrix}
\]

\[
C' = \begin{bmatrix}
\text{pq x mn}
\end{bmatrix}
\begin{bmatrix}
\text{pq x 1}
\end{bmatrix}
\begin{bmatrix}
\text{mn x 1}
\end{bmatrix}
\]

\[
T^T
\]

\[
P'
\]
Example

conventional photograph with light coming from right

dual photograph as seen from projector’s position
Properties of the transport matrix

- little interreflection $\rightarrow$ sparse matrix
- many interreflections $\rightarrow$ dense matrix
- convex object $\rightarrow$ diagonal matrix
- concave object $\rightarrow$ full matrix

Can we create a dual photograph entirely from diffuse reflections?
Dual photography from diffuse reflections

the camera’s view
The relighting problem

- subject captured under multiple lights
- one light at a time, so subject must hold still
- point lights are used, so can’t relight with cast shadows

Paul Debevec’s Light Stage 3
The 6D transport matrix
The 6D transport matrix
The advantage of dual photography

- capture of a scene as illuminated by different lights cannot be parallelized
- capture of a scene as viewed by different cameras can be parallelized
Measuring the 6D transport matrix
Relighting with complex illumination

- step 1: measure 6D transport matrix $T$
- step 2: capture a 4D light field
- step 3: relight scene using captured light field

\[
\begin{bmatrix}
C'
\end{bmatrix} =
\begin{bmatrix}
T^T
\end{bmatrix}
\begin{bmatrix}
P'
\end{bmatrix}
\]
Running time

- The different rays within a projector can in fact be parallelized to some extent.

- This parallelism can be discovered using a coarse-to-fine adaptive scan.

- Can measure a 6D transport matrix in 5 minutes.
Can we measure an 8D transport matrix?

projector array

camera array

scene
$C = \begin{bmatrix} T \\ P \end{bmatrix}$

$\begin{bmatrix} \text{mn x 1} \\ \text{mn x pq} \\ \text{pq x 1} \end{bmatrix}$

http://graphics.stanford.edu