3D Computer Vision

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DFKI – Deutsches Forschungszentrum für Künstliche Intelligenz

http://av.dfki.de
Augmented Vision

- Head: Prof. Didier Stricker
- Founded in July 2008
- 35 PhDs and fulltime researchers
- 3 strongly connected research areas:
  - Computer Vision
  - Virtual and Augmented Reality
  - Body Sensor Networks
3D Computer Vision

• Course Policies:
  - Lecture: Wednesday, 8:15 – 9:45
  - “SWS: 2V + 1Ü”
  - Credit points: 4 CP
  - Language: English
3D Computer Vision

- **Topics of the Lecture:**
  - Introduction: What is a camera?
  - Camera model and camera calibration
  - 2D-image transformation (mapping) and panorama
  - Fitting and parameter estimation
  - Two cameras: epipolar geometry and triangulation
  - Multiple view reconstruction
  - Depth maps and multiple view stereo reconstruction
  - Structured light: laser, coded light

Images

Camera pose

3D reconstruction

Texturing
3D Computer Vision

• Exercises:
  ▪ Homework assignments consisting of
    ▪ theoretical part (questions) and
    ▪ practical part (Python implementations)
    to be solved and submitted in small groups (by email).
  ▪ Accompanying supervised exercise sessions: two hours every two weeks (discussion of last exercise, presentation/preparation of current exercise).

  ▪ Room: PC-32/411 (computer pool) → SCI account required
  ▪ Time: Monday, 17:00 to 19:00
  ▪ Exam: Oral / written exam (depending on number of students). In order to qualify, a minimum average score of 60% in the exercises is required.
  ▪ Check the Python introduction on the web-site.

  ▪ NO EXERCISES NEXT WEEK – WE WILL ANNOUNCE THEM IN THE LECTURE AND ONLINE!
Contact

• Prof. Didier Stricker

• Exercises:
  ▪ Tewodros Habtegebrial: tewodros_amberbir.habtegebrial@dfki.de
  ▪ Torben Fetzer: torben.fetzer@dfki.de
  ▪ Fangwen Shu: fangwen.shu@dfki.de

• All material will be available at:
  http://ags.cs.uni-kl.de/teaching/ → Lectures
Augmented Vision - Maintenance
Augmented Vision
- Markerless Tracking

Augmented Vision for Maintenance, 2004

Tourism, 2002
Augmented Things
- The universal interface for the Internet of Things

Tracking of an industrial machine.
Autonomous Driving
- The universal interface for the Internet of Things
Autonomous Driving
- Slam
Driving Assistant System
- Human Pose Estimation
3D Reconstruction - Structure from Motion

Input Images

Multiple View Stereo

Structure from Motion

3D Model
3D Reconstruction
- from Spherical Images

http://youtu.be/Hg792_Mh1Cg
3D Reconstruction - from Spherical Images

Ricoh Theta camera 360°, image stack (1cm, 60 images)
3D Reconstruction
- from Spherical Images

Ricoh Theta camera 360°, image stack (1cm, 60 images)
3D Reconstruction
- from Spherical Images

Ricoh Theta camera 360°, image stack (1cm, 60 images)
3D Reconstruction - from Spherical Images

Ricoh Theta camera 360°, image stack (1cm, 60 images)
Full 3D Human Body Scanning with a Single Kinect

Paper ID: 1751
Today: The Camera
Overview

• **The pinhole projection model**
  - Qualitative properties
  - Perspective projection matrix

• **Cameras with lenses**
  - Depth of focus
  - Field of view
  - Lens aberrations

• **Digital cameras**
  - Types of sensors
  - Color
How do we see the world?

• Let’s design a camera
  ▪ Idea 1: Put a piece of film in front of an object.
  ▪ Do we get a reasonable image?
Add a barrier to block off most of the rays
- This reduced blurring.
- The opening is known as the **aperture**.
Pinhole Camera Model

- **Pinhole projection model**
  - Captures pencil of rays – all rays through a single point.
  - The point is called **center of projection** (focal point).
  - The image if formed on the image plane.
What have we lost?

- Angles
- Distances (lengths)
Projection Properties

- **Many-to-one**
  - Any point along same ray maps to the same image point.

- **Points → Points**
  - But only defined for points in front of focal plane.

- **Lines → Lines**
  - Collinearity is preserved.
  - But lines through focal point project to points.

- **Planes → Planes (or half-planes)**
  - But planes through focal point project to lines.
Projection Properties

- Parallel lines converge at a vanishing point
  - Each direction in space has its own vanishing point.
  - But parallel lines, which are parallel to the image plane remain parallel.
  - All directions in the same plane have vanishing points on the same line.

- How do we construct the vanishing point / line?
One-Point Perspective

- Masaccio, *Trinity*, Santa Maria Novella, Florence, 1425-28
- First consistent use of perspective in western art?
Perspective Distortion

- Problem for architectural photography: Converging verticals.
- What does a sphere project to?

Image source: F. Durand
Perspective Distortion
Perspective Distortion

- The exterior columns appear bigger.
- The distortion is not due to lens flaws.
- Problem pointed out by Da Vinci.
Perspective Distortion
- People
The coordinate system

- We use the pinhole camera model as approximation of the projection.
- Put the optical center (focal point) at the origin (O).
- Put the image plane ($\Pi'$) in front of O.

Source: J. Ponce, S. Seitz
Modelling Projection

- **Projection equations**
  - Compute intersection of ray from $P = (x, y, z)^T$ to $O$ with $\Pi'$.
  - Derived using similar triangles.
  - We get the projection by throwing out the last coordinate:

$$P = (x, y, z)^T \rightarrow (f' \frac{x}{z}, f' \frac{y}{z})^T = P'$$

Source: J. Ponce, S. Seitz
Homogeneous Coordinates

\[ P = (x, y, z)^\top \rightarrow \left( f' \frac{x}{z}, f' \frac{y}{z} \right)^\top = P' \]

- Is this a linear transformation? \( \rightarrow \) No, division by \( z \) is nonlinear.
- Trick: Add one more coordinate:

\[
\begin{pmatrix}
  x \\
  y \\
  1
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  x \\
  y \\
  1
\end{pmatrix}
\text{homogeneous image coordinates}
\]

\[
\begin{pmatrix}
  x \\
  y \\
  z \\
  1
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  x \\
  y \\
  1
\end{pmatrix}
\text{homogeneous scene coordinates}
\]

- Converting \textbf{from} homogeneous coordinates:

\[
\begin{pmatrix}
  x \\
  y \\
  w
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  \frac{x}{w} \\
  \frac{y}{w} \\
  \frac{w}{w}
\end{pmatrix}
\]

\[
\begin{pmatrix}
  x \\
  y \\
  z \\
  w
\end{pmatrix}
\rightarrow
\begin{pmatrix}
  \frac{x}{w} \\
  \frac{y}{w} \\
  \frac{z}{w}
\end{pmatrix}
\]
Perspective Projection Matrix

- Projection is a matrix multiplication using homogeneous coordinates:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & \frac{1}{f'} & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
x \\
y \\
z \\
1
\end{pmatrix} =
\begin{pmatrix}
x \\
y \\
z \\
\frac{1}{f'}
\end{pmatrix}
\Rightarrow
\begin{pmatrix}
f' & x \\
f' & y \\
f' & \frac{z}{f'}
\end{pmatrix}
\]

Divide by the third coordinate

- In practice: Lots of coordinate transformations…

\[
\begin{pmatrix}
2D \\
point \\
(3x1)
\end{pmatrix} =
\begin{pmatrix}
\text{Camera} \\
to \\
\text{pixel} \\
\text{coord.} \\
trans. \\
\text{matrix} \\
(3x3)
\end{pmatrix}
\begin{pmatrix}
\text{Perspective} \\
\text{projection} \\
\text{matrix} \\
(3x4)
\end{pmatrix}
\begin{pmatrix}
\text{World} \\
to \\
camera \\
coord. \\
trans. \\
\text{matrix} \\
(4x4)
\end{pmatrix}
\begin{pmatrix}
3D \\
point \\
(4x1)
\end{pmatrix}
\]
Building a Real Camera
Camera Obscura

- Basic principle known to Mozi (470-390 BCE), Aristotle (384-322 BCE)
- Drawing aid for artists: Described by Leonardo da Vinci (1452-1519)

Gemma Frisius, 1558

Source: A. Efros
Home-made Pinhole Camera

Why so blurry?

http://www.debevec.org/Pinhole/
Shrinking the Aperture

- Why not making the aperture as small as possible?
  - Less light gets through.
  - Diffraction effects...
Shrinking the Aperture

Source: A. Efros
The Reason for Lenses
• A lens focuses the light onto the film.
  ▪ Rays passing through the center are not deviated.
A lens focuses the light onto the film.

- Rays passing through the center are not deviated.
- All parallel rays converge to one point, the focal point, on a plane located at a distance $f$ (focal length) to the lens.
A lens focuses the light onto the film.

- There is a specific distance at which objects are in focus.
- Other points project to a circle of confusion in the image.
Thin lens Formula

- Similar triangles everywhere!
Thin lens Formula

- Similar triangles everywhere!

\[ \frac{y'}{y} = \frac{D'}{D} \]
Thin lens Formula

- Similar triangles everywhere!

\[
\frac{y'}{y} = \frac{D'}{D} \quad \text{and} \quad \frac{y'}{y} = \frac{D' - f}{f}
\]
Thin lens Formula

- Any point satisfying the thin lens equation is in focus:

\[ \frac{1}{D'} + \frac{1}{D} = \frac{1}{f} \]
Depth of Field

http://www.cambridgeincolour.com/tutorials/depth-of-field.htm
How can we control the depth of field?

- Changing the aperture size affects the depth of field (DOF).
  - A smaller aperture increases the range in which the object is approximately in focus.
  - But small aperture reduces the amount of light – need to increase exposure.


$f/5.6$

$f/32$
Varying the aperture

Large aperture = small DOF

Small aperture = large DOF
Field of View (Zoom)

From London and Upton
Field of View (Zoom)

From London and Upton
Field of View (FOV)

- FOV depends on focal length and size of the camera retina
  - Smaller FOV = larger focal length

\[ \varphi = \tan^{-1}\left(\frac{d}{2f}\right) \]
Field of View / Focal Length

Large FOV, small focal length, camera close to car

Small FOV, large focal length, camera far from the car

Sources: A. Efros, F. Durand
Field of View / Focal Length
- Same effect for faces

wide-angle  standard  telephoto

Sources: A. Efros, F. Durand
Real Lenses
Lens Flaws
- Chromatic Aberration

- Lens has different refractive indices for different wavelengths:
  - Causes color fringing.

Near Lens Center

Near Lens Outer Edge
Lens Flaws - Vignetting
Lens Flaws - Radial Distortion

- Caused by imperfect lenses.
- Deviations are most noticeable for rays that pass through the edge of the lens.
Digital Cameras

- A digital camera replaces film with a sensor array.
  - Each cell in the array is a light-sensitive diode that converts photons to electrons.
  - Two common types:
    - Charge coupled Devices (CCD)
    - Complementary metal oxide semiconductor (CMOS)
CCD vs. CMOS

- **CCD** transmits the charge across the chip and reads it at one corner of the array. An analog-to-digital converter (ADC) then converts each pixel's value into a digital value by measuring the amount of charge at each photosite and then converting that measurement to binary form.

- **CMOS** uses several transistors at each pixel to amplify and move the charge using more traditional wires. The CMOS signal is digital, so it needs no ADC.

High Dynamic Range Images

- **CCD / CMOS** have a given dynamic range for capturing the luminance of the scene – **LDR** cameras (Low Dynamic Range).

- Problem: The dynamic range of the scene illumination is higher than the dynamic range of the camera.

- It results:
  - under exposed areas
  - saturation areas
High Dynamic Range Images

- **High Dynamic Range Image (HDR)**
  - Standard RGB images are encoded over 8 bit integer (255 values)
  - HDR: 12-, 16- or 32-bit floating point

www.OpenEXR.com
Color Sensing in Camera - Color Filter Array

Estimate missing components from neighboring values (demosaicing)

Why more green?

Human Luminance Sensitivity Function

Source: Steve Seitz
Color Sensing in Camera - Prism

- **3 CCD camera:**
  - Requires three chips and precise alignment.
  - More expensive.
Issues with Digital Cameras

- **Noise**
  - Low light is where you most notice noise.
  - Light sensitivity (ISO) / noise tradeoff.

- **Resolution**
  - Requires higher quality lens.
  - Noise issues

- **In-camera processing**
  - Oversharpening can produce halos.

- **RAW vs. compressed**
  - File size vs. quality tradeoff

- **Blooming**
  - Charge overflowing into neighboring pixels.

- **Color artifacts**
  - Purple fringing from microlenses, artifacts from Bayer patterns
  - White balance

- **More info online**
Historical Context

- **Pinhole model:** Mozi (470-390 BCE), Aristotle (384-322 BCE)
- **Principles of optics (including lenses):**
  - Alhacen (965-1039 CE)
- **Camera obscura:** Leonardo da Vinci (1452-1519), Johann Zahn (1631-1707)
- **First photo:** Joseph Nicephore Niepce (1822)
- **Daguerréotypes** (1839)
- **Photographic film** (Eastman, 1889)
- **Cinema** (Lumière Brothers, 1895)
- **Color Photography** (Lumière Brothers, 1908)
- **Television** (Baird, Farnsworth, Zworykin, 1920s)
- **First consumer camera with CCD:** Sony Mavica (1981)
- **First fully digital camera:** Kodak DCS100 (1990)
Thank You!