Fundamentals of Image Processing and Computer Vision

Prof. Dr. Davide Scaramuzza

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Today’s Class

• Introductions
• What is Computer Vision?
• Example of Vision Applications
• Specifics of this course
• Image Formation
A Bit about Me
My Research Background

Perception
- Visual Odometry and SLAM
- Camera calibration
- Sensor fusion

Field and Service Robotics
- Self driving cars
- Autonomous micro helicopters

[JFR’10, AURO’11, RAM’14]
[JFR’11, IJCV’11, PAMI’13, ICRA’14]
A Bit about Me

http://rpg.ifi.uzh.ch
Andreasstrasse 15, 2nd floor
Current Research Activities

Real-time Monocular Dense Reconstruction

Visual SLAM for multiple MAVs

Aggressive maneuvers with onboard cameras

Air-ground collaboration
Current Research Activities

Real-time Monocular Dense Reconstruction

Monocular dense reconstruction in real-time from a hand-held camera

Stage-set from Gruber et al., "The City of Sights", ISMAR'10.
Current Research Activities

Vision-controlled Micro Aerial Vehicles
Current Research Activities

Multi-robot collaboration
Current Research Activities

Air-ground collaboration
Now it’s your turn!

• What’s your name?
• What are you studying?
• Why are you interested in computer vision?
Today’s Class

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What is computer vision?

Done?
What is computer vision?

• Automatic extraction of “meaningful” information from images and videos
What kind of information can be extracted from an image?

Semantic information

Geometric information
Vision Demo?

Terminator 2

we’re not quite there yet....
Can computers match (or beat) human vision?

Yes and no (but mostly no!)

- computers can be better at “easy” things
- humans are much better at “hard” things
Human perception has its shortcomings...

For example, how do we recognize a face? From its features (mouth, nose, eyes) or from the head as a whole?

Human perception has its shortcomings...

For example, how do we recognize a face? From its features (mouth, nose, eyes) or from the head as a whole?

Computers are better at recognizing faces!

Human perception has its shortcomings...
Human perception has its shortcomings...

What is the difference in brightness?

Courtesy E. Adelson
http://web.mit.edu/persci/people/adelson/checkershadow_downloads.html
Why study computer vision?

- Relieve humans of boring, easy tasks
- Enhance human abilities: human-computer interaction, visualization
- Perception for robotics / autonomous agents
- Organize and give access to visual content
- Vision is difficult
  - Half of primate cerebral cortex is devoted to visual processing
Vision in humans

- **Vision** is our most powerful sense in aiding our perception of the 3D world around us.
- Retina is \( \sim 1000 \text{mm}^2 \). Contains millions of **photoreceptors** (120 mil. rods and 7 mil. Cones for color sampling)
- Provides **enormous** amount of information: data-rate of \(~3\text{GBytes/s}\)
  \( \Rightarrow \) a large proportion of our brain power is dedicated to processing the signals from our eyes
- How many Megapixels does the human eye have? \( > 500\text{Megapixels!} \)

http://webvision.med.utah.edu/sretina.html
Why is vision hard?

• How do we go from an array of numbers to recognizing a fruit?
Why is vision hard?

- Challenges: Viewpoint variations
Why is vision hard?

- Challenges: Illumination
Why is vision hard?

- Challenges: Motion
Why is vision hard?

- Challenges: object intra-class variations
Why is vision difficult?

• Challenges: ambiguities
Why is vision difficult?

- Challenges: inherent ambiguities. Many different 3D scenes could give rise to a particular 2D picture.
Origins of computer vision

Related disciplines

- Graphics
- Image processing
- Robotics
- Artificial intelligence
- Machine learning
- Cognitive science

Computer vision
Computer Vision vs Computer Graphics

Images → Computer Vision → Model → Computer Graphics

This course

Inverse problems: analysis and synthesis.

Prof. Dr. Renato Pajarola
Computer Graphics (FS15)
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• RPG Research Activities
Earth viewers (3D modeling)

Google Earth, Microsoft’s Bing Maps
Microsoft Photosynth

http://labs.live.com/photosynth/

Based on Photo Tourism technology developed by Noah Snavely, Steve Seitz, and Rick Szeliski
Photo Tourism overview

System for interactive browsing and exploring large collections of photos of a scene. Computes viewpoint of each photo as well as a sparse 3d model of the scene.
Photo Tourism overview
Optical character recognition (OCR)

Technology to convert scanned docs to text

- If you have a scanner, it probably came with OCR software

Digit recognition, AT&T labs
http://www.research.att.com/~yann/

License plate readers
http://en.wikipedia.org/wiki/Automatic_number_plate_recognition
Face detection

• Most new digital cameras and phones now detect faces
  – Canon, Sony, Fuji, ...
Smile detection?

The Smile Shutter flow

Imagine a camera smart enough to catch every smile! In Smile Shutter Mode, your Cyber-shot® camera can automatically trip the shutter at just the right instant to catch the perfect expression.
Object recognition (in supermarkets)

LaneHawk by EvolutionRobotics
“A smart camera is flush-mounted in the checkout lane, continuously watching for items. When an item is detected and recognized, the cashier verifies the quantity of items that were found under the basket, and continues to close the transaction. The item can remain under the basket, and with LaneHawk, you are assured to get paid for it… “
Vision-based biometrics

Who is she?
Vision-based biometrics

“How the Afghan Girl was Identified by Her Iris Patterns” Read the story
Login without a password...

Fingerprint scanners on many new laptops, other devices

Face recognition systems now beginning to appear more widely
http://www.sensiblevision.com/

Fingerprint scanner in iPhone 5S
Object recognition (in mobile phones)

• This is becoming real:
  – Lincoln Microsoft Research
  – Point & Find, Nokia
  – SnapTell.com (Amazon)
  – Google Goggles
Special effects: shape and motion capture
Sports

• Augmented Reality

The AC Liveline system is bringing augmented reality to sailing.

2013 America’s Cup
For football event, see also (Libero Vision) (Swiss company) [http://www.vizrt.com/products/viz_libero/](http://www.vizrt.com/products/viz_libero/)
3D Reconstruction: Multi-View Stereo

YouTube Video
3D Reconstruction: Multi-View Stereo

YouTube Video
Automotive safety

- **Mobileye**: Vision systems in high-end BMW, GM, Volvo models
  - Pedestrian collision warning
  - Forward collision warning
  - Lane departure warning
  - Headway monitoring and warning
Vision-based interaction (and games)

Nintendo Wii has camera-based IR tracking built in.

Digimask: put your face on a 3D avatar.
Vision-based interaction: Xbox Kinect
3D Reconstruction: Kinect Fusion

YouTube Video
Vision in space

**NASA'S Mars Exploration Rover Spirit** captured this westward view from atop a low plateau where Spirit spent the closing months of 2007.

Vision systems (JPL) used for several tasks

- Panorama stitching
- 3D terrain modeling
- Obstacle detection, position tracking
- For more, read “**Computer Vision on Mars**” by Matthies et al.
Medical imaging

3D imaging
MRI, CT

Image guided surgery
Grimson et al., MIT
Dacuda’s mouse scanner

- Technical Consultant for Dacuda AG, inventor of the world’s first mouse scanner, currently distributed by LG: SmartScan LG LSM100
Google Tango Phone
Current state of the art

• You just saw examples of current systems.
  – Many of these are less than 5 years old

• This is a very active research area, and rapidly changing
  – Many new apps in the next 5 years

• To learn more about vision applications and companies
  – David Lowe maintains an excellent overview of vision companies
    • http://www.cs.ubc.ca/spider/lowe/vision.html
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Computer Vision at University of Zurich

Prof. Dr. Davide Scaramuzza
Fundamentals of Image Processing and Computer Vision (HS15)

Prof. Dr. Renato Pajarola
Computer Graphics (FS15)

Prof. Dr. Kevan A. Martin
Computational Vision (Computation in Neural Systems: Biological and Computational Vision) (FS15)
Organization of this Course

- **Room:** BIN-1-D.25 - Binzmuhlestrasse 14
- **Time:**
  - **Lectures:** 10:15 to 12:00 every week;
  - **Exercises:** 14:15 to 15:45 every 2 weeks (please bring your laptop)
- **Course website:** [http://rpg.ifi.uzh.ch/teaching.html](http://rpg.ifi.uzh.ch/teaching.html)
## Course Schedule

For updates, slides, and additional material:  [http://rpg.ifi.uzh.ch/teaching.html](http://rpg.ifi.uzh.ch/teaching.html)

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<th>Lecture number</th>
<th>Date</th>
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<th>Description of the lecture/exercise</th>
<th>Lecturer</th>
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<tr>
<td>01</td>
<td>18.09.2014</td>
<td>10:15 - 12:00</td>
<td>Introduction</td>
<td>Scaramuzza</td>
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<td>02</td>
<td>25.09.2014</td>
<td>10:15 - 12:00</td>
<td>Image Formation</td>
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<td>03</td>
<td>02.10.2014</td>
<td>10:15 - 12:00</td>
<td>Filtering and edge detection</td>
<td>Scaramuzza</td>
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<td></td>
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<td>14:15 – 15:45</td>
<td>Exercise: Matlab intro + filtering exercise</td>
<td>Forster</td>
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<tr>
<td>04</td>
<td>09.10.2014</td>
<td>10:15 - 12:00</td>
<td>Line Detection and Point Feature Detectors 1</td>
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<td>05</td>
<td>16.10.2014</td>
<td>10:15 - 12:00</td>
<td>Point Feature Detectors 2</td>
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<td>14:15 – 15:45</td>
<td>Exercise: Harris detector</td>
<td>Forster</td>
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<td>06</td>
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<td>Multiple-view geometry 1 (Epipolar geometry and stereo)</td>
<td>Gallego</td>
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<td>Multiple-view geometry 2 (Two-view Structure from Motion and RANSAC)</td>
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<td>Exercise: 8-point algorithm and RANSAC</td>
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<td>Multiple-view geometry 3 (n-view Structure-from-Motion and Bundle Adjustment)</td>
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<td>09</td>
<td>13.11.2014</td>
<td>10:15 - 12:00</td>
<td>Shape from X, Photometric Stereo, Multi-view Photometric Stereo, Optical flow</td>
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<td>14:15 – 15:45</td>
<td>Exercise Photometric stereo</td>
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<td>3D Reconstruction (Multi-view Stereo)</td>
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<td>Exercise: Lucas-Kanade tracker</td>
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<td>Recognition</td>
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<td>Paper presentations</td>
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<td>14:15 – 15:45</td>
<td>Exercise: Recognition with Bag of Words</td>
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<td>15</td>
<td>15.01.2015</td>
<td>08:00 – 18:00</td>
<td>Oral exams</td>
<td>ALL</td>
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Exercises

- Every two weeks
- Bring **your own laptop**
- Have **Matlab** pre-installed
  - You can download it from the UZH website: [http://www.id.uzh.ch/dl/sw/angebote_4.html](http://www.id.uzh.ch/dl/sw/angebote_4.html)
  - You will need to install all the toolboxes included in the license.
  - Info on how to setup the license can be found here: [http://www.s3it.uzh.ch/software/matlab/](http://www.s3it.uzh.ch/software/matlab/)

Have you used Matlab before?
Recommended Textbook


• Can be freely downloaded from http://szeliski.org/Book/

• Other books:
  – An Invitation to 3D Vision: Y. Ma, S. Soatto, J. Kosecka, S.S. Sastry
  – Multiple view Geometry: R. Hartley and A. Zisserman
  – Autonomous Mobile Robots: R. Siegwart, I.R. Nourbakhsh, D. Scaramuzza -> Chapter 4
Instructors

• Main Instructor
  – Davide Scaramuzza

• Co-instructors and Exercises
  – Reza Sabzevari
    PhD at Italian Institute of Technology
  – Guillermo Gallego
    PhD at Georgia Tech
  – Christian Forster
    PhD student
Office receiving times

- Tuesdays and Thursdays from 2 to 4pm
  AND 2.26 (preferred: announce by email)
Prerequisites

- This course is appropriate as a first course for Bachelor and Master students with basic knowledge of
  - Linear algebra
  - Matrix calculus

- The course does not assume prior imaging experience, computer vision, image processing, or graphics
Grading and Exam

• 40%: presentation of two papers in front of the class (last two lectures: Dec. 11 and 18)

• 60%: oral exam (20 minutes) – Date: Jan 15, 2015

• For those who won’t make a paper presentation
  – Oral exam (30 minutes)

• In addition, strong class and exercise participation can offset negative performance in any one of the above components.
Class Participation

- Class participation includes
  - showing up
  - being able to articulate key points from last lecture
Course Topics

• Principles of image formation
• Image filtering
• Feature detection
• Multi-view geometry
• Structure from motion
• Visual recognition
Course Topics

• Principles of image formation
  – Perspective projection
  – Camera calibration
Course Topics

• Image filtering

Low-pass filtered image  High-pass filtered image
Course Topics

• Feature detection and matching
Course Topics

• Multi-view geometry and 3D reconstruction
Course Topics

• Multi-view geometry and 3D reconstruction

San Marco square, Venice
14,079 images, 4,515,157 points
Course Topics

• Visual recognition

Instance recognition, large-scale alignment

Sliding window detection

Part-based models
Today’s Class

• Introductions
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• Image Formation
Let’s get started: Image formation

• How are objects in the world captured in an image?
The camera

Sony Cybershot WX1
How to form an image

- Place a piece of film in front of an object
  ➔ Do we get a reasonable image?
Pinhole camera

- Add a barrier to block off most of the rays
  - This reduces blurring
  - The opening known as the aperture
Camera obscura

In Latin, means ‘dark room’

- Basic principle known to Mozi (470-390 BC), Aristotle (384-322 BC)
- Drawing aid for artists: described by Leonardo da Vinci (1452-1519)
- Image is inverted
- Depth of the room (box) is the effective focal length

"Reinerus Gemma-Frisius, observed an eclipse of the sun at Louvain on January 24, 1544, and later he used this illustration of the event in his book De Radio Astronomica et Geometrica, 1545. It is thought to be the first published illustration of a camera obscura..." Hammond, John H., The Camera Obscura, A Chronicle
Pinhole camera model

- Pinhole model:
  - Captures beam of rays – all rays through a single point
  - The point is called Center of Projection or Optical Center
  - The image is formed on the Image Plane

- We will use the pinhole camera model to describe how the image is formed
Camera obscura at home

Figure 1 - A lens on the window creates the image of the external world on the opposite wall and you can see it every morning, when you wake up.

Sketch from http://www.funsci.com/fun3_en/sky/sky.htm

http://www.youtube.com/watch?v=B2aOs8RWntg
Home-made pinhole camera

What can we do to reduce the blur?
Shrinking the aperture

Why not make the aperture as small as possible?
Shrinking the aperture

Why not make the aperture as small as possible?

- Less light gets through (must increase the exposure)
- Diffraction effects...
Why use a lens?

- *The ideal pinhole:* only one ray of light reaches each point on the film ⇒ image can be very dim
- Making the pinhole bigger (i.e. aperture)...
- A lens can focus multiple rays coming from the same point
Image formation using a converging lens

- A lens focuses light onto the film
- Rays passing through the optical center are not deviated
A lens focuses light onto the film.
Rays passing through the optical center are not deviated.
All rays parallel to the **Optical Axis** converge at the **Focal Point**.
Thin lens equation

Find a relationship between $f, z$ and $e$
Thin lens equation

- Any object point satisfying this equation is in focus

"Thin lens equation"

\[
\begin{align*}
\frac{B}{A} &= \frac{e}{z} \\
\frac{B}{A} &= \frac{e-f}{f} = \frac{e}{f} - 1
\end{align*}
\]

Similar Triangles:

- \[\frac{B}{A} = \frac{e}{z}\]
- \[\frac{B}{A} = \frac{e-f}{f} = \frac{e}{f} - 1\]
“In focus”

- There is a specific distance from the lens, at which world points are “in focus” in the image.
- Other points project to a “blur circle” in the image.
Blur Circle

- Object is out of focus $\Rightarrow$ Blur Circle has radius: $R = \frac{L\delta}{2e}$
  
  - A minimal $L$ (pinhole) gives minimal $R$
  - To capture a ‘good’ image: adjust camera settings, such that $R$ remains smaller than the image resolution
The Pin-hole approximation

• What happens if \( z \gg f \) ?

\[ \frac{1}{f} + \frac{1}{e} \approx \frac{1}{e} \Rightarrow f \approx e \]

• We need to adjust the image plane such that objects at infinity are in focus
The Pin-hole approximation

- What happens if $z \gg f$?

- We need to adjust the image plane such that objects at infinity are in focus.

\[
\frac{1}{f} = \frac{1}{z} \approx \frac{1}{e} \Rightarrow f \approx e
\]

\[
\approx 0
\]
The Pin-hole approximation

• What happens if \( z \gg f \) ?

• We need to adjust the image plane such that objects at infinity are in focus

\[
\frac{h'}{h} = \frac{f}{z} \Rightarrow h' = \frac{f}{z} h
\]

• The dependence of the apparent size of an object on its depth (i.e. distance from the camera) is known as perspective
Perspective Projection

- For convenience, the image plane is usually represented in front of C such that the image preserves the same orientation (i.e. not flipped)
- A camera does not measure distances but angles!

\[ C = \text{optical center} = \text{center of the lens} \]

\[ O = \text{principal point} \]

\[ Z_c = \text{optical axis} \]

Image plane (CCD)

\[ P_c \]
Playing with Perspective

• Perspective gives us very strong depth cues
  ⇒ hence we can perceive a 3D scene by viewing its 2D representation (i.e. image)
• An example where perception of 3D scenes is misleading:

“Ames room”
A clip from "The computer that ate Hollywood" documentary.
Dr. Vilayanur S. Ramachandran.
Perspective effects

- Far away objects appear smaller
Perspective effects
Projective Geometry

What is lost?

• Length
• Angles
Projective Geometry

What is preserved?

• Straight lines are still straight
Vanishing points and lines

Parallel lines in the world intersect in the image at a “vanishing point”
Vanishing points and lines

Parallel lines in the world intersect in the image at a “vanishing point”
Vanishing points and lines

Vanishing Line

Vanishing Point

Vanishing Point
Today’s Class

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• Other camera parameters
Pinhole size / aperture

How does the size of the aperture affect the image we’d get?

Fig. 5.96 The pinhole camera. Note the variation in image clarity as the hole diameter decreases. [Photos courtesy Dr. N. Joel, UNESCO.]
Pinhole vs. lens

- A lens focuses light onto the film
Cameras with lenses

- A lens focuses parallel rays onto a single focal point.
- It allows the camera to gather more light, while keeping focus.
- Makes the pinhole perspective projection practical.
- What happens if we decrease/increase the aperture?
Focus and depth of field

- Depth of field (DOF) is the distance between the nearest and farthest objects in a scene that appear acceptably sharp in an image.

- Although a lens can precisely focus at only one distance at a time, the decrease in sharpness is gradual on each side of the focused distance, so that within the DOF, the unsharpness is imperceptible under normal viewing conditions.
Focus and depth of field

• How does the aperture affect the depth of field?

• A smaller aperture increases the range in which the object is approximately in focus
Varying the aperture

Large aperture = small DOF

Small aperture = large DOF
Field of view depends on focal length

- As $f$ gets smaller, image becomes more wide angle
  - more world points project onto the finite image plane
- As $f$ gets larger, image becomes more narrow angle
  - smaller part of the world projects onto the finite image plane
Field of view

Angular measure of portion of 3d space seen by the camera
Field of view

\[ \tan \frac{\theta}{2} = \frac{W}{2f} \quad \text{or} \quad f = \frac{W}{2} \left[ \tan \frac{\theta}{2} \right]^{-1} \]

Smaller FOV = larger Focal Length
Field of View (Zoom) = Cropping

From London and Upton
Vignetting

• Tendency of the brightness of the image to fall off towards the edge of the image

• Why and how can we remove it?
Vignetting

• “natural”: the light that reaches the patch on the image sensor is reduced by an amount that depends on angle $\alpha$

• “mechanical”: occlusion of rays near the periphery of the lens elements in a compound lens
Chromatic aberration

What causes it?
Chromatic aberration

- Because the index of refraction for glass varies slightly as a function of wavelength, light of different colors focuses at slightly different distances (and hence also with slightly different magnification factors).

- In order to reduce chromatic aberration, most photographic lenses today are compound lenses made of different glass elements (with different coatings).
Digital cameras

• Film $\rightarrow$ sensor array
• Often an array of charge coupled devices
• Each CCD/CMOS is light sensitive diode that converts photons (light energy) to electrons
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)
An example camera datasheet

**mvBlueFOX-IGC / -MLC**

**Technical Details**

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<th>Sensor size (optical)</th>
<th>Pixel size (μm)</th>
<th>Frame rate</th>
<th>Sensor technology</th>
<th>Readout type</th>
<th>ADC resolution / output in bits</th>
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<td>CMOS</td>
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1 High Dynamic Range (HDR) mode supported
2 Software trigger supported

Sample: mvBlueFOX-IGC200wG means version with housing and 752 x 480 CMOS gray scale sensor.
mvBlueFOX-MLC200wG means single-board version without housing and with 752 x 480 CMOS gray scale sensor.

**Hardware Features**

<table>
<thead>
<tr>
<th>Gray scale / Color</th>
<th>Gray scale (G) / Color (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interface</th>
<th>USB 2.0 (up to 480 Mbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image formats</td>
<td>Mono8, Mono10, BayerGR8, BayerGR10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Triggers</th>
<th>External hardware based (optional), software based (depending on the sensor) or free run</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size w/o lens (W x H x L)</td>
<td>mvBlueFOX-IGC: 39.8 x 39.8 x 16.5 mm</td>
</tr>
<tr>
<td>mvBlueFOX-MLC: 35 x 33 x 25 mm (without lens mount)</td>
<td>approx. 80 g</td>
</tr>
<tr>
<td>Permissible ambient temperature</td>
<td>Operation: 0 → 45 °C / 30 to 80 % RH</td>
</tr>
<tr>
<td>Lens mounts</td>
<td>Back focus adjustable C/CS-mount lens holder / C-mount, CS-mount or optional S-mount</td>
</tr>
<tr>
<td>Digital I/Os</td>
<td>mvBlueFOX-IGC (optional)</td>
</tr>
<tr>
<td>mvBlueFOX-MLC</td>
<td>1 / 1 opto-isolated</td>
</tr>
<tr>
<td>1 / 1 opto-isolated or 2 / 2 TTL compliant</td>
<td></td>
</tr>
<tr>
<td>Conformity</td>
<td>CE, FCC, RoHS</td>
</tr>
<tr>
<td>Driver</td>
<td>mvIMPACT Acquire SDK</td>
</tr>
<tr>
<td>Operating systems</td>
<td>Windows®, Linux® - 32 bit and 64 bit</td>
</tr>
<tr>
<td>Special features</td>
<td>Micro-PLC, automatic gain / exposure control, binning, screw lock connectors</td>
</tr>
</tbody>
</table>
Digital images

Pixel Intensity: [0, 255] (8 bits)

im[176][201] has value 164
im[194][203] has value 37
Color sensing in digital cameras

The Bayer pattern (Bayer 1976) places green filters over half of the sensors (in a checkerboard pattern), and red and blue filters over the remaining ones.

This is because the luminance signal is mostly determined by green values and the visual system is much more sensitive to high frequency detail in luminance than in chrominance.

The process of interpolating the missing color values so that we have valid RGB values for all the pixels is known as demosaicing.
Color sensing in digital cameras

Bayer grid

Estimate missing components from neighboring values (demosaicing)

A newer chip design by Foveon (http://www.foveon.com) stacks the red, green, and blue sensors beneath each other, but it has not yet gained widespread adoption.
Color images:
RGB color space
... but there are also many other color spaces... (e.g., YUV)
Summary (things to remember)

- Definition of computer vision
- Computer-vision challenges
- Computer-vision applications
- Camera obscura
- Thin-lens model
- Perspective effects and Ames room
- Definitions
  - Chromatic aberration
  - Depth of field
  - Digital-image-formation pipeline
  - Bayer grid
- Readings for today: 1.1, 1.2, 2.2.3, 2.3, and page 76
Next time

- Image Formation
- Readings for next lecture: 2.1