**Capture Devices**

- **Cameras**
  - Traditional, omnidirectional
  - Satellite-based, telescopes, microscopes
- **Scanners**
  - Laser, structured-light
- **Radar**
  - Traditional, Doppler, ground-penetrating, sound-based (sonar), light-based (lidar)
- **Atmospheric**
  - Radio-based
- **Medical**
  - X-ray, MRI, CAT, Electron microscope, STM

**Cameras**

- Traditional camera
  - Pinhole Camera Model
    - Problems: aberrations, distortions
    - Tradeoff between aperture, shutter speed, focus, dynamic range
- Calibration
  - Fit an assumed camera model to an actual camera
- Omnidirectional cameras
  - Single camera, multiple cameras, rotating camera designs
- Localization and pose estimation
  - Where is the camera relative to the object or environment

**Optical Systems**

- **Dioptric**
  - All elements are refractive (lenses)
- **Catoptric**
  - All elements are reflective (mirrors)
- **Catadioptric**
  - Elements are refractive and reflective (mirrors + lenses)

**A Thin Lens System (Dioptric)**

\[ \frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \]

**“Classic” Pinhole Camera**

\[ f \]

\[ d \]

\[ f \]

\[ d \]
Aberrations

- A “real” lens system does not produce a perfect image
- Aberrations are caused by imperfect manufacturing and by our approximate models
  - Lenses typically have a spherical surface
    - Aspherical lenses would better compensate for refraction but are more difficult to manufacture
  - Typically 1st order approximations are used
    - Remember \( \sin \Omega = \Omega - \Omega^3/3! + \Omega^5/5! - \ldots \)
    - Thus, thin-lens equations only valid if \( \sin \Omega \approx \Omega \)

Spherical Aberration

- Deteriorates the axial-image

Coma

- Deteriorates off-axial bundles of rays

Most common aberrations:
- Spherical aberration
- Coma
- Astigmatism
- Curvature of field
- Chromatic aberration
- Distortion
Astigmatism and Curvature of Field
- Produces multiple (two) images of a single object point

Chromatic Aberration
- Caused by wavelength dependent refraction
  - Apochromatic lenses (e.g., RGB) can help

Distortion
- Radial (and tangential) image distortions
  - Example radial distortions

Radial Distortion
- $(x, y)$ pixel before distortion correction
- $(x', y')$ pixel after distortion correction
- Let $r = (x^2 + y^2)^{-1}$
  - Then
    - $x' = x(1 - \Delta r/r)$
    - $y' = y(1 + \Delta r)$
    - where $\Delta r = k_0$r + $k_1$r^3 + $k_2$r^5 + ...
  - Finally,
    - $x' = x(1 - k_0 - k_1r^2 - k_2r^4 - ...)$
    - $y' = y(1 - k_0 - k_1r^2 - k_2r^4 - ...)$

Taking a picture...

Exposures
- An “exposure” is when the CCD is exposed to the scene, typically for a brief amount of time and with a particular set of camera parameters
- The characteristics of an “exposure” are determined by multiple factors, in particular:
  - Camera aperture
    - Determines amount of light that shines onto CCD
  - Camera shutter speed
    - Determines time during which aperture is “open” and light is shined onto CCD
Exposures

Digital Camera vs. "Film" Camera

- **Charge-Coupled Device (CCD)**
  - Image plane is a CCD array instead of film
  - CCD arrays are typically ¼ or ½ inch in size
  - CCD arrays have a pixel resolution (e.g., 640x480, 1024x1024)
  - CCD Cameras have a maximum "frame rate", usually determined by the hardware and bandwidth

- **Number of CCDs**
  - 3: each CCD captures only R, G, or B wavelengths
  - 1: the single CCD captures RGB simultaneously, reducing the resolution by 1/3 (kinda)

- **Video**
  - Interlaced: only "half" of the horizontal lines of pixels are present in each frame
  - Progressive scan: each frame has a full set of pixels

The simplest 1-CCD camera in town

Dynamic Range

- The dynamic range of an image is the maximum difference between the darkest and brightest spot of an image

- Typical images have very limited dynamic range
  - A typical JPEG, TIFF, BMP image has 8 bits per color or a maximum dynamic range of 256 per color channel (256:1)

- The real-world has much higher dynamic range
  - A typical scene can have 100,000:1 dynamic range

Dynamic Range

- Example images

100,000:1 250,000:1

Dynamic Range

- To compensate for this, researchers either
  - Ignore the problem
  - Use more bits per color channel (the camera must support this!)
  - Use images with multiple exposures and combine them; the "combined image" can then be tone-mapped back to an 8-bit image
High Dynamic Range Images

- Short exposure
- Tone-mapped image
- Long exposure

Aperture vs. Shutter Speed

- How do you deal with low-light scenes?
- How do you deal with fast moving objects?
- How do you produce crisp/focused images?

- Small aperture
  - Crisp images, requires lots of light
- Fast shutter speed
  - Crisp images for moving objects, requires lots of light
- Large aperture
  - Low-light ok, images can be blurry
- Slow shutter speed
  - Can produce crisp images in low light but camera/objects cannot move

Some Videos...

- Fiat Lux (SIGGRAPH '99)
  - Rendering synthetic images in a real environment using high-dynamic-range techniques