Robot Sensing: Perception

METR 4202: Advanced Control & **Robotics**

Dr Surya Singh -- Lecture # 5

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Schedule

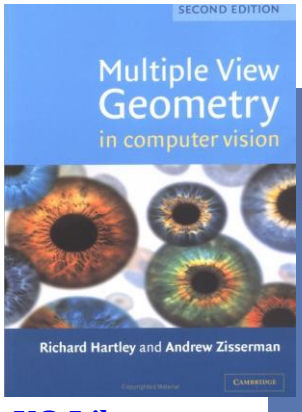
Week	Date	Lecture (W: 12:05-1:50, 50-N201)
1	29-Jul	Introduction
2	5-Aug	Representing Position & Orientation & State (Frames, Transformation Matrices & Affine Transformations)
3	12-Aug	Robot Kinematics Review (& *Ekka Day*)
4	19-Aug	Robot Dynamics
5	**26-Aug**	**Robot Sensing: Perception**
6	2-Sep	Robot Sensing: Multiple View Geometry
7	9-Sep	Robot Sensing: Feature Detection (as Linear Observers)
8	16-Sep	Probabalistic Robotics: Localization
9	23-Sep	**Quiz** & Guest Lecture (SLAM?)
	30-Sep	*Study break*
10	7-Oct	Motion Planning
11	14-Oct	State-Space Modelling
12	21-Oct	Shaping the Dynamic Response
13	28-Oct	LQR + Course Review

Announcements!

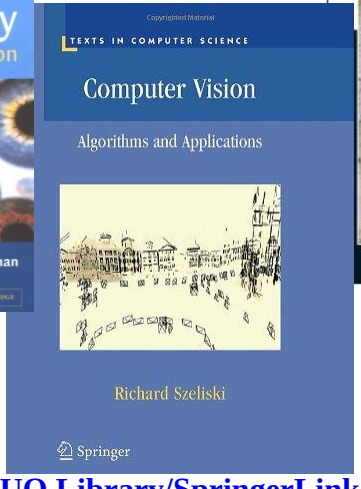
- Reading for Next Week:
  - **Computer Vision: Algorithms and Applications [UQ]**
  - The Condensation Paper!
    - M. Isard and A. Blake. "Condensation—conditional density propagation for visual tracking." *International Journal of Computer Vision* **29(1)**:5-28, 1998.

- Lab 2:
  - Hand Tracking
  - Almost at hand!
- Lab 1:
  - Thanks!
  - Please see the Platypus "solution" for tips on FK/IK.

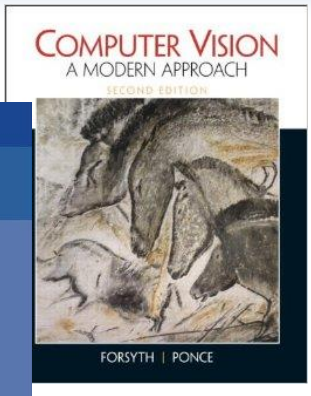
Reference Material



UQ Library
(ePDF)



UQ Library/SpringerLink



UQ Library
(Hardcopy)

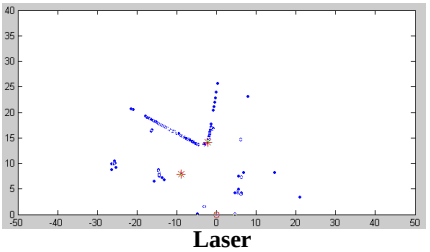
Quick Outline

- Frames
- Kinematics

➔ "Sensing Frames" (in space) ➔ Geometry in Vision

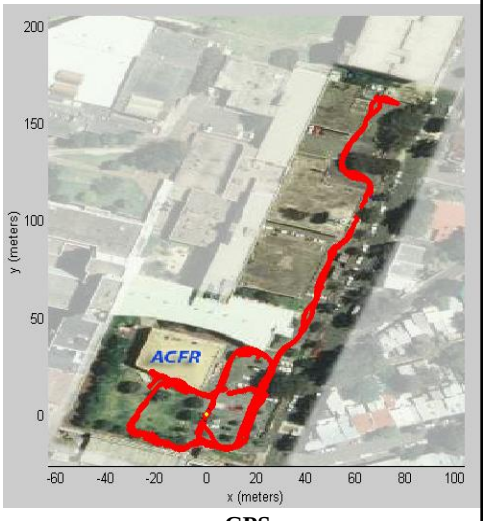
1. **<u>Perception → Camera Sensors</u>**
   1. Image Formation
      ➔ "Computational Photography"
   2. Calibration
   3. Features
   4. Stereopsis and depth
   5. Optical flow

Sensor Information: Mostly **(but not only)** Cameras!



Laser

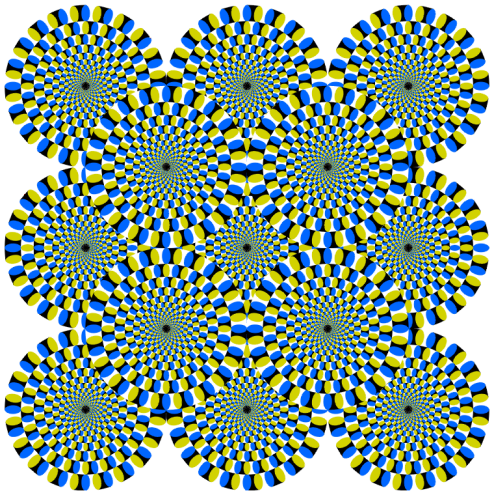
Vision/Cameras



GPS

Perception

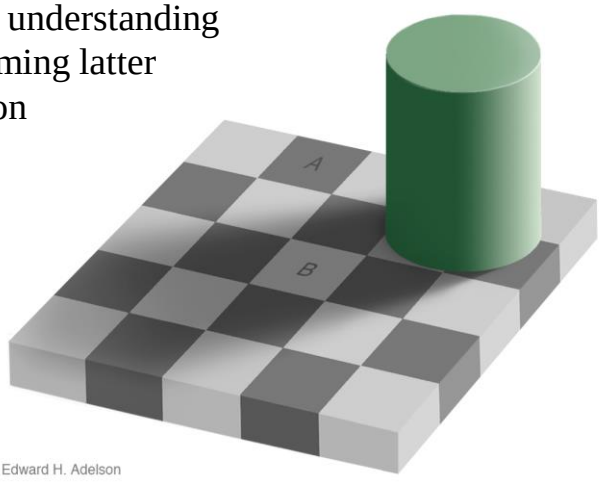
- Making Sense from Sensors



http://www.michaelbach.de/ot/mot_rotsnake/index.html

Perception

- Perception is about understanding the image for informing latter robot / control action

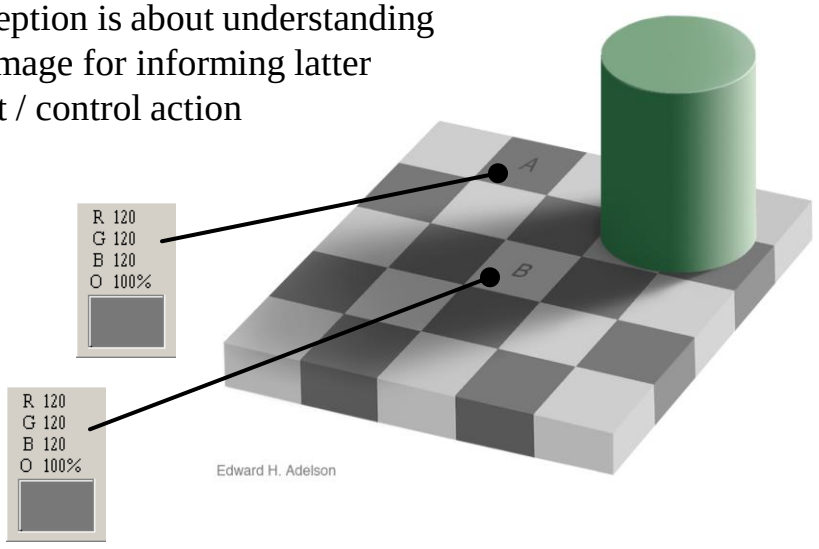


Edward H. Adelson

http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html

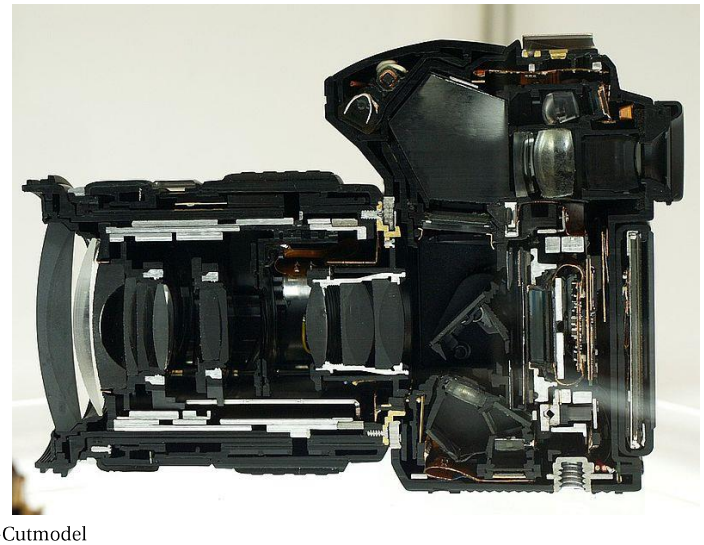
Perception

- Perception is about understanding the image for informing latter robot / control action



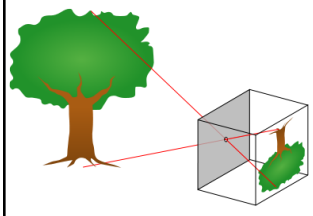
http://web.mit.edu/persci/people/adelson/checkershadow_illusion.html

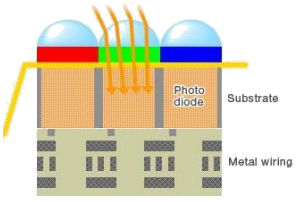
Cameras



Wikipedia, E-30-Cutmodel

Cameras: A 3D ⇒ 2D Photon Counting Sensor*





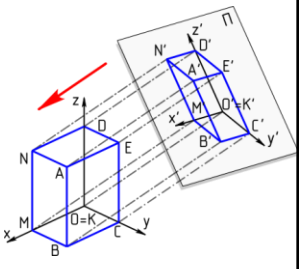
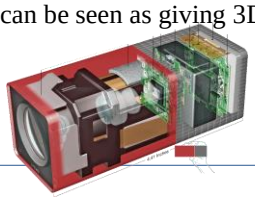


Image Formation ⇒ Image Sensing ⇒ (Re)Projection

Sources: Wikipedia, Pinhole Camera, Sony sensor, Wikipedia, Graphical projection,

* Well Almost… RGB-D and Light-Field cameras can be seen as giving 3D ⇒ 3D



Camera Image Formation: 3D↦2D ⇒ **Perspective!**

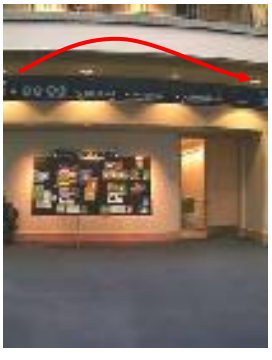
Camera Image Formation "Aberrations"[I]: Lens Optics (Aperture / Depth of Field)

$$N = \frac{f}{\#} = \frac{f}{d}$$

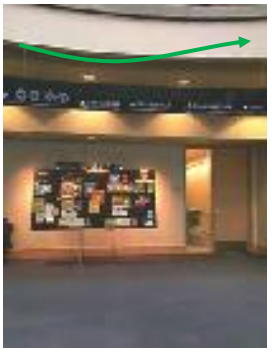
http://en.wikipedia.org/wiki/File:Aperture_in_Canon_50mm_f1.8_II_lens.jpg

Camera Image Formation "Aberrations"[II]: Lens Distortions

Barrel



Pincushion



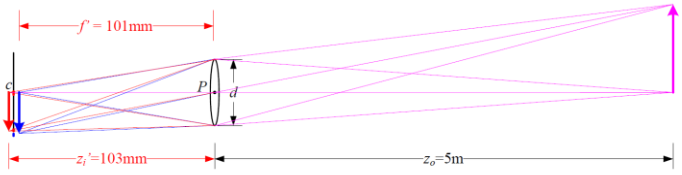
Fisheye

➔ Explore these with `visualize_distortions` in the Camera Calibration Toolbox

Fig. 2.1.3 from Szeliski, *Computer Vision: Algorithms and Applications*

Camera Image Formation "Aberrations" [II]: Lens Optics: Chromatic Aberration

- Chromatic Aberration:

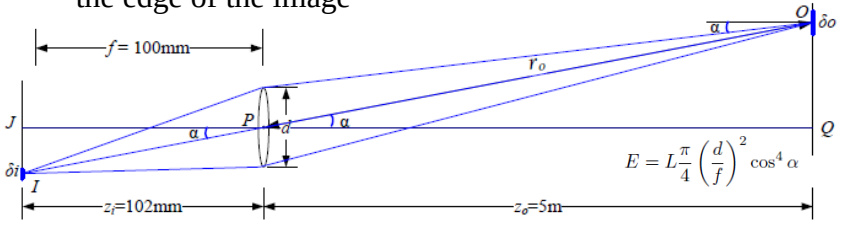


  - In a lens subject to chromatic aberration, light at different wavelengths (e.g., the red and blur arrows) is focused with a different focal length f' and hence a different depth z_i, resulting in both a geometric (in-plane) displacement and a loss of focus

Sec. 2.2 from Szeliski, *Computer Vision: Algorithms and Applications*

Camera Image Formation "Aberrations" [III]: Lens Optics: Vignetting

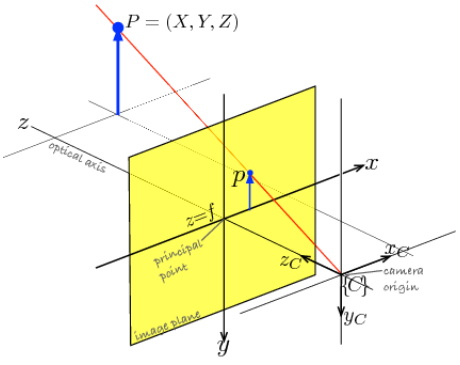
- Vignetting:
  - The tendency for the brightness of the image to fall off towards the edge of the image



  - The amount of light hitting a pixel of surface area δi depends on the square of the ratio of the aperture diameter d to the focal length f, as well as the fourth power of the off-axis angle α, $\cos^4 \alpha$

Sec. 2.2 from Szeliski, *Computer Vision: Algorithms and Applications*

Image Formation – Single View Geometry



$$\frac{Y}{Z} = \frac{y}{f} \quad \frac{X}{Z} = \frac{x}{f}$$

$$x = \frac{fX}{Z}, y = \frac{fY}{Z}$$

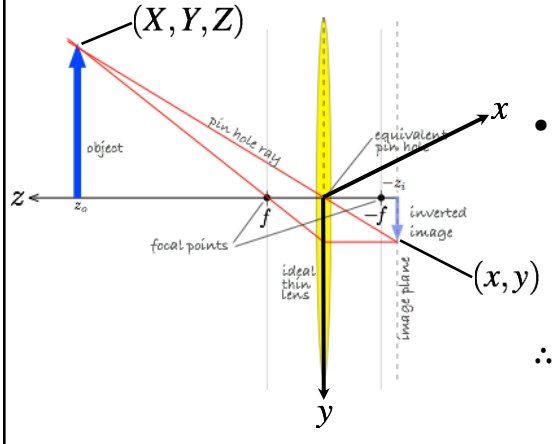
$$(X,Y,Z) \mapsto (x,y)$$

$$\mathbb{R}^3 \mapsto \mathbb{R}^2$$

Image and Slide from: Corke, Ch. 11

Image Formation: (Thin-Lens) Projection model

- $x = \frac{fX}{Z}, y = \frac{fY}{Z}$

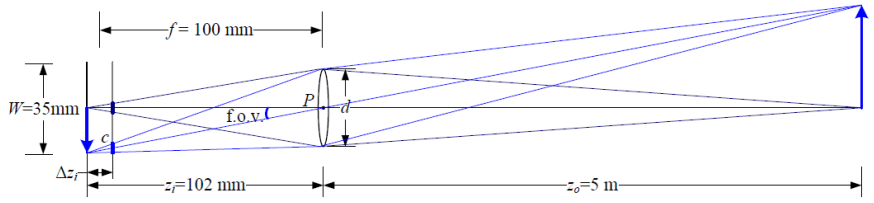


- $\frac{1}{z_0} + \frac{1}{z_1} = \frac{1}{f}$

$\therefore$ as $z_0 \to \infty$, $z_i \to f$

Image and Slide from: Corke, Ch. 11

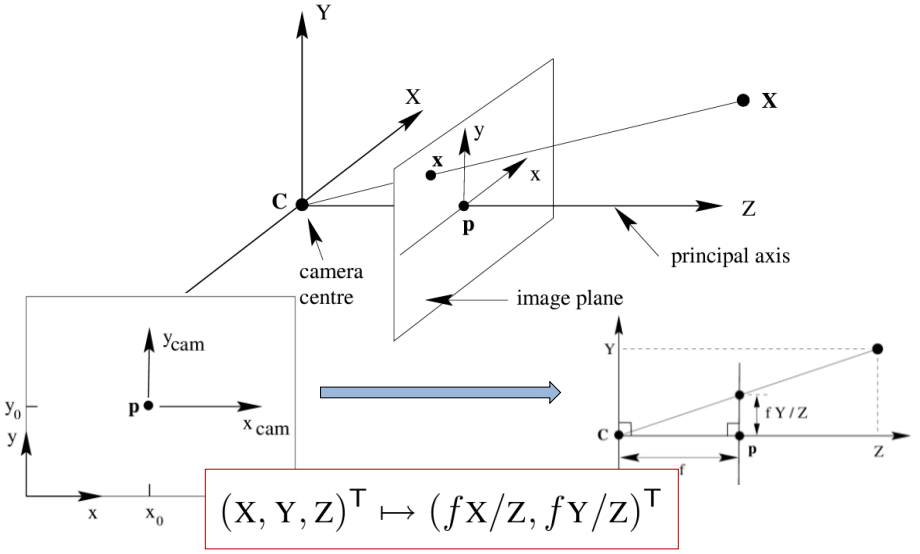
Image Formation: Simple Lens Optics ≅ Thin-Lens



$$\frac{1}{z_0} + \frac{1}{z_1} = \frac{1}{f}$$

Sec. 2.2 from Szeliski, *Computer Vision: Algorithms and Applications*

Image Formation – Single View Geometry [I]



$$(X, Y, Z)^\top \mapsto (fX/Z, fY/Z)^\top$$

Hartly & Zisserman, Ch. 6

Image Formation – Single View Geometry [II]

➔ Camera Projection Matrix

$$\begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix} \mapsto \begin{pmatrix} fX + Zp_x \\ fY + Zp_y \\ Z \end{pmatrix} = \begin{bmatrix} f & & p_x & 0 \\ & f & p_y & 0 \\ & & 1 & 0 \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \\ 1 \end{pmatrix}$$

world camera Intrinsics

- x = Image point
- $\mathbf{X}$ = World point
- K = Camera Calibration Matrix

$$\mathrm{K} = \begin{bmatrix} f & & p_x \\ & f & p_y \\ & & 1 \end{bmatrix}$$

$$\mathbf{x} = \mathrm{K}[\mathrm{I} \mid \mathbf{0}]\mathbf{X}_{\mathrm{cam}}.$$

➔Perspective Camera as:

where: P is **3**×4 and of **rank 3**

$$\mathrm{P} = \mathrm{K}[\mathrm{R} \mid \mathbf{t}]$$

Calibration matrix

- Is this form of K good enough?
- non-square pixels (digital video)
- skew
- radial distortion

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} \sim \begin{bmatrix} f & 0 & u_c \\ 0 & f & v_c \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = \mathbf{K}\ \mathbf{X}_c$$

$$\begin{bmatrix} fa & s & u_c \\ 0 & f & v_c \\ 0 & 0 & 1 \end{bmatrix} = \mathbf{K}$$

From Szeliski, *Computer Vision: Algorithms and Applications*

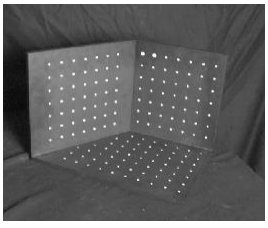
Calibration

See: *Camera Calibration Toolbox for Matlab*
(http://www.vision.caltech.edu/bouguetj/calib_doc/)

- Intrinsic: Internal Parameters
  - **Focal length:** The focal length in pixels.
  - **Principal point:** The principal point
  - **Skew coefficient:**
    The skew coefficient defining the angle between the x and y pixel axes.
  - **Distortions:** The image distortion coefficients (radial and tangential distortions) (typically two quadratic functions)
- Extrinsics: Where the Camera (image plane) is placed:
  - **Rotations:** A set of 3x3 rotation matrices for each image
  - **Translations:** A set of 3x1 translation vectors for each image

Camera calibration

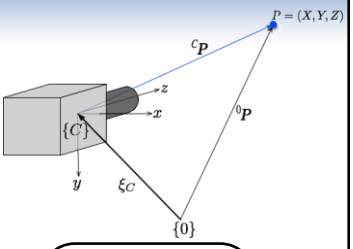
- Determine camera parameters from known 3D points or calibration object(s)
- internal or intrinsic parameters such as focal length, optical center, aspect ratio:
  what kind of camera?
- external or extrinsic (pose) parameters:
  where is the camera?
- How can we do this?



From Szeliski, *Computer Vision: Algorithms and Applications*

Complete camera model

$$\begin{pmatrix}\tilde{x}\\ \tilde{y}\\ \tilde{z}\end{pmatrix} = \begin{pmatrix}f & 0 & 0 & 0\\ 0 & f & 0 & 0\\ 0 & 0 & 1 & 0\end{pmatrix}\begin{pmatrix}X\\ Y\\ Z\\ 1\end{pmatrix}$$



extrinsic parameters

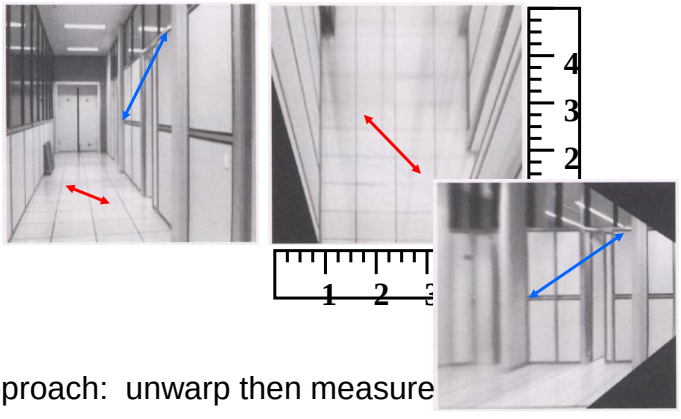
$$\begin{pmatrix}\tilde{u}\\ \tilde{v}\\ \tilde{w}\end{pmatrix} = \underbrace{\underbrace{\begin{pmatrix}\frac{1}{\rho_u} & 0 & u_0\\ 0 & \frac{1}{\rho_v} & v_0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}f & 0 & 0 & 0\\ 0 & f & 0 & 0\\ 0 & 0 & 1 & 0\end{pmatrix}}_{\mathbf{K}}\begin{pmatrix}\mathbf{R} & t\\ \mathbf{0}_{1\times 3} & 1\end{pmatrix}^{-1}}_{\mathbf{C}}\begin{pmatrix}X\\ Y\\ Z\\ 1\end{pmatrix}$$

intrinsic parameters

camera matrix

Image and Slide from: Corke, Ch. 11

Measurements on Planes
(You can not just add a tape measure!)



Approach: unwarp then measure

Slide from Szeliski, *Computer Vision: Algorithms and Applications*

Features -- Colour Features

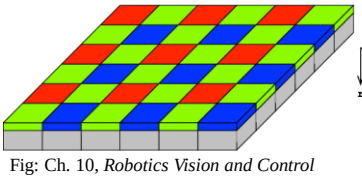
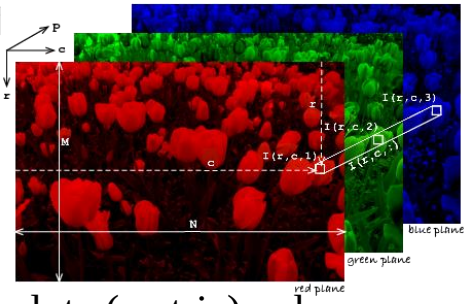


Fig: Ch. 10, *Robotics Vision and Control*

Bayer Patterns



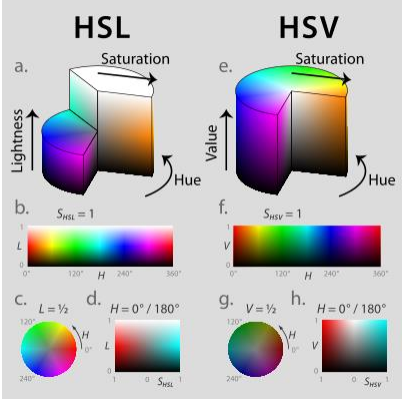
- RGB is **NOT** an absolute (metric) colour space

Also!

- **RGB** (display or additive colour) does not map to **CYMK** (printing or subtractive colour) without calibration
- **Y-Cr-Cb** or **HSV** does not solve this either

Colour Spaces

- HSV



Source: Wikipedia – HSV and YCrCb

- YCrCb

➔Gamma Corrected Luma (Y) + Chrominance

➔BW → Colour TVs : Just add the Chrominance

➔γ Correction: CRTs γ=2.2-2.5

$$\begin{aligned} Y' &= 16 + (65.481 \cdot R' + 128.553 \cdot G' + 24.966 \cdot B') \\ C_B &= 128 + (-37.797 \cdot R' - 74.203 \cdot G' + 112.0 \cdot B') \\ C_R &= 128 + (112.0 \cdot R' - 93.786 \cdot G' - 18.214 \cdot B') \end{aligned}$$

- L*ab

How to get the Features? Still MANY Ways

- Canny edge detector:

Subtractive (CMYK) & Uniform (L*ab) Color Spaces

- $C = W - R$
- $M = W - G$
- $Y = W - B$

- $K = -W$ ☺

- A Uniform color space is one in which the distance in coordinate space is a fair guide to the significance of the difference between the two colors

- Start with RGB → CIE XYZ (Under Illuminant D65)

$$L^\star = 116(Y/Y_n)^{(1/3)} - 16$$
$$a^\star = 500\left[(X/X_n)^{(1/3)} - (Y/Y_n)^{(1/3)}\right]$$
$$b^\star = 200\left[(Y/Y_n)^{(1/3)} - (Z/Z_n)^{(1/3)}\right]$$