Design of Control Systems
Vision systems

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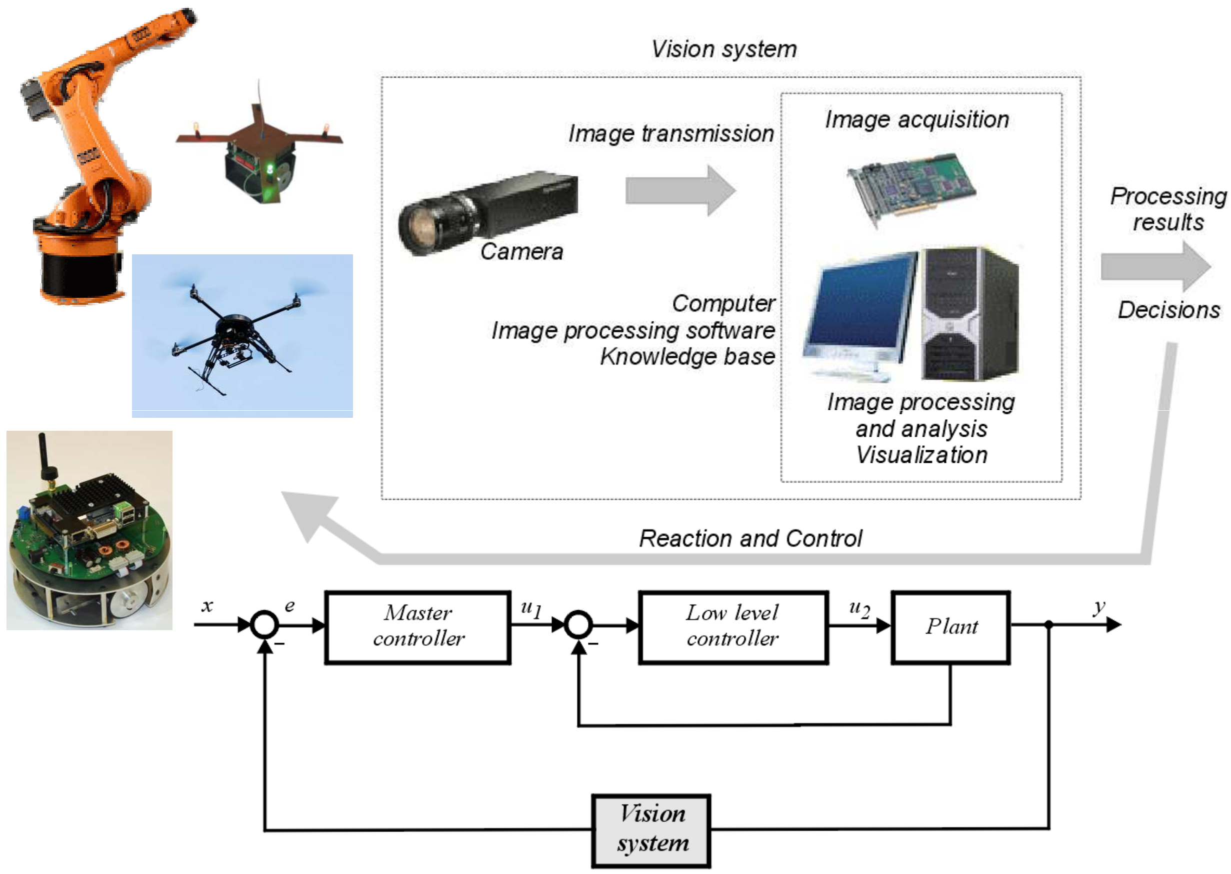
Visual feedback in control systems



Vision systems in robotics

Applications of vision systems in robotics

- in industry, for parts recognition and positioning, quality inspection of products,
- as a vision feedback in control system for position and orientation measurement in task space,
- in medicine for teleoperation and control of robot assistant helping during surgery,
- humanoid robots – vision systems can be a smart sensor substituting human eyes (stereovision),
- navigation in unknown environment, determining relative geometric relations between objects and map building of the environment – SLAM,
- for mobile robot teleoperation, exploring, monitoring or patrol of wide areas of land,
- in robot assisted rescue missions.

The use of vision feedback in robot control

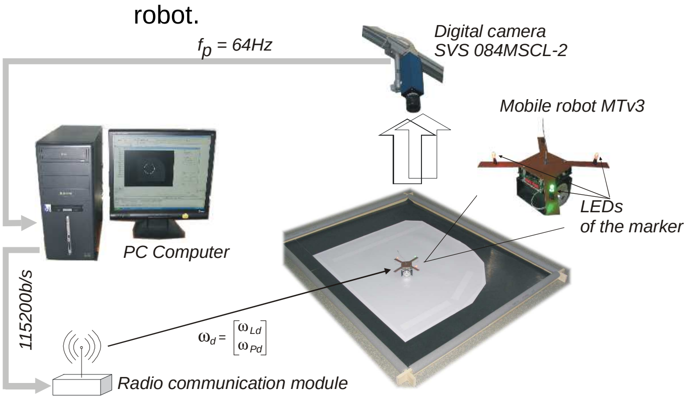
Camera configurations relative to the robot

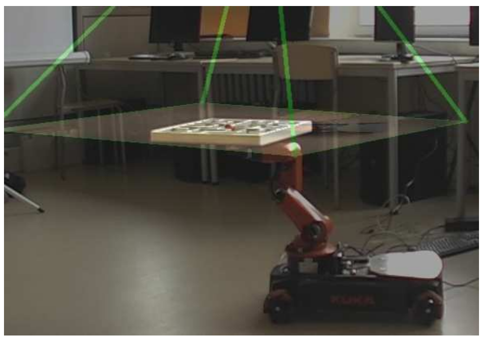
- Eye-in-hand configuration, camera is mounted on the end-effector or on the mobile robot:
  - geometrical relationship between the camera and task space is changing during the motion,
  - typically transformation between camera and robot coordinate system is known or can be determined,
  - information from the camera is local, in some cases is hard to determine what causes the changes in the image (movement of the camera or environment),
  - small movement of the robot can produce significant changes in the image,
  - for mobile robots, this configuration doesn't limit working space,
  - for manipulators two cases can be distinguished: camera can observe the end-effector or end-effector is not observed by the camera.

The use of vision feedback in robot control

Camera configurations relative to the robot

- Fixed camera configuration, camera is fixed in the space and can observe movement of the robot in working area:
  - the camera should be placed to allow to observe fixed working area with the robot, working space is limited by camera field of view, only for stationary applications,
  - the advantages are: fixed field of view and fixed relationships between camera coordinates and working space, information from the camera can be easily calculated as global information,
  - this configuration can produce problems related to covering some parts of working area or objects by the robot.





The use of vision feedback in robot control

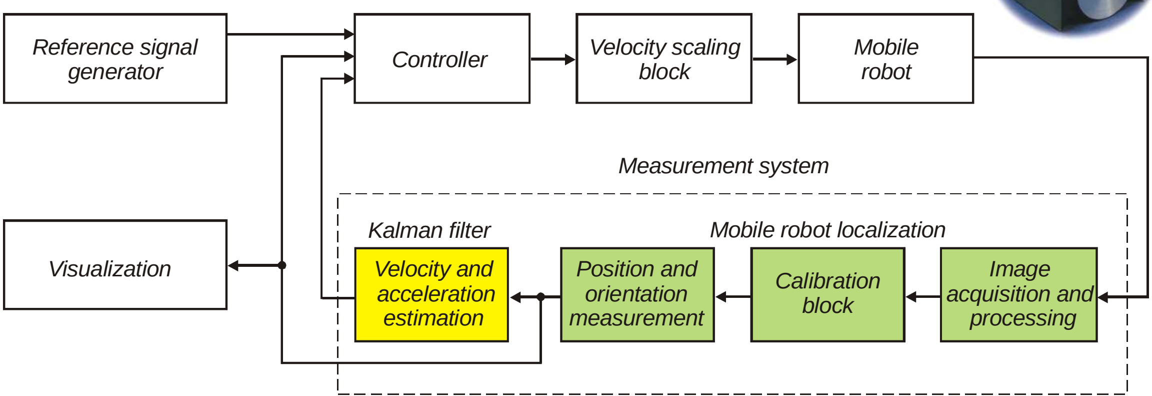
Using vision system for control purpose require vision error signal. It can be calculated base on the measurement resulting from image analysis.

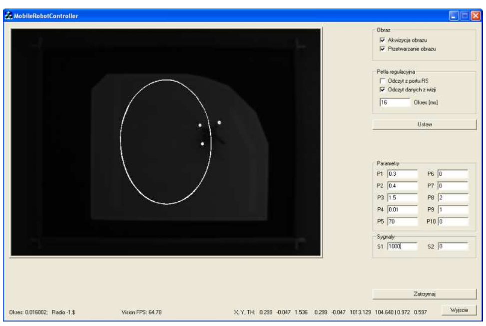
- Position-based control – control error is calculated in task space:
  - more intuitive, allows to use classic control laws (in Cartesian space) but requires complex feature extraction in the image and following recalculation from image space to task space,
  - typically is more time consuming, requires accurate camera calibration and determining relationship between camera coordinate system and Cartesian task space coordinate system,
  - there is no direct affect to camera field of view in eye-in-hand configuration.

- Image-based control – control error is calculated in image space:
  - typically lower computational complexity, there is no need to complete scene reconstruction and recalculation to task space, more robust to camera calibration inaccuracy,
  - this control ensures that tracked image features don't go out the camera view,
  - there is no direct control to the range of robots movements; minimizing errors in image space can cause significant displacement of the camera placed on the robot manipulator,
  - problem with singularities resulting from 3D space projection to the plane of the image.

The use of vision feedback in robot control

Example of control system structure for the mobile robot





The use of vision feedback in robot control

Common problems and limitations:

- acquisition, transfer and processing huge amount of data (digital image transmission e.g. image 640x480, color, 25Hz -> about 23MB/s; FullHD 1920x1080, color, 25Hz -> about 148 MB/s),
- problems with imperfections of image information:
  - resulting from image acquisition process (like noises in the image, optical and chromatic distortions etc.), it can be minimized by technical improvements,
  - nature of the image acquisition process (projection from 3D to 2D space, illumination).
- computational complexity of image processing algorithms and large memory requirements,
- time consuming to obtain complete information from the image,
- problems with real-time working with high frequency,
- the need of taking into account in design of image processing algorithms:
  - domain knowledge,
  - common sense knowledge, especially during machine learning from image information – besides using formal techniques there is need to use some heuristic methods and algorithms for specific problems.

The use of vision feedback in robot control

Relationship with others domains:

- Image Processing
- Pattern Recognition
- Computer Vision
- Robotics
- Signal Processing
- Computer Graphics
- Image Understanding
- Artificial Intelligence
- Machine Learning
- Cognitive Science
- Algebra (e.g. Morphology)
- Statistics

Computer vision for control purpose

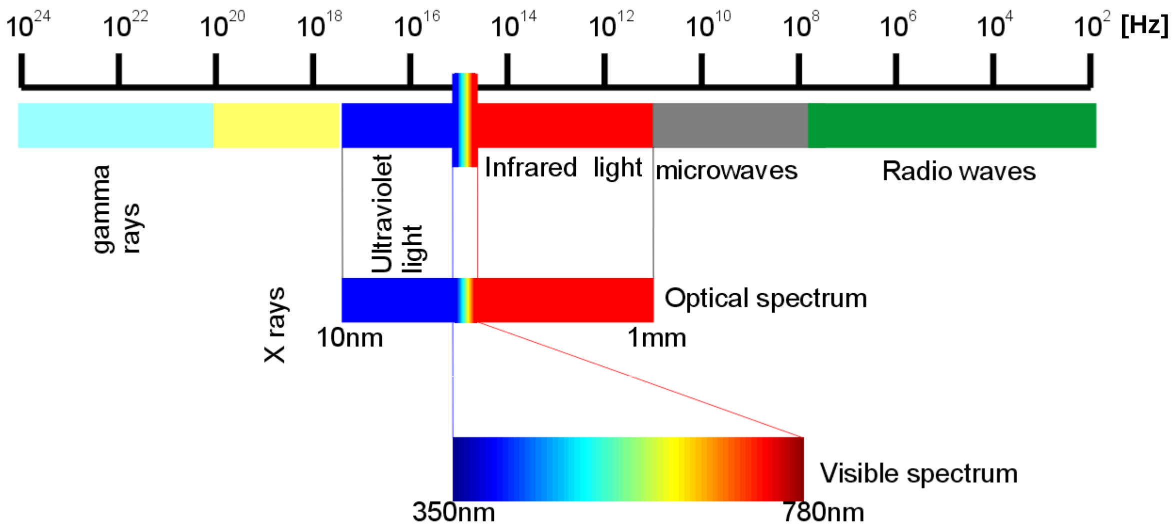
Process steps of computer vision:

- image acquisition,
- image preprocessing,
- image segmentation,
- feature extraction and description,
- feature analysis and recognition,
- results interpretation and recalculation,
- use of the results.

Why use?

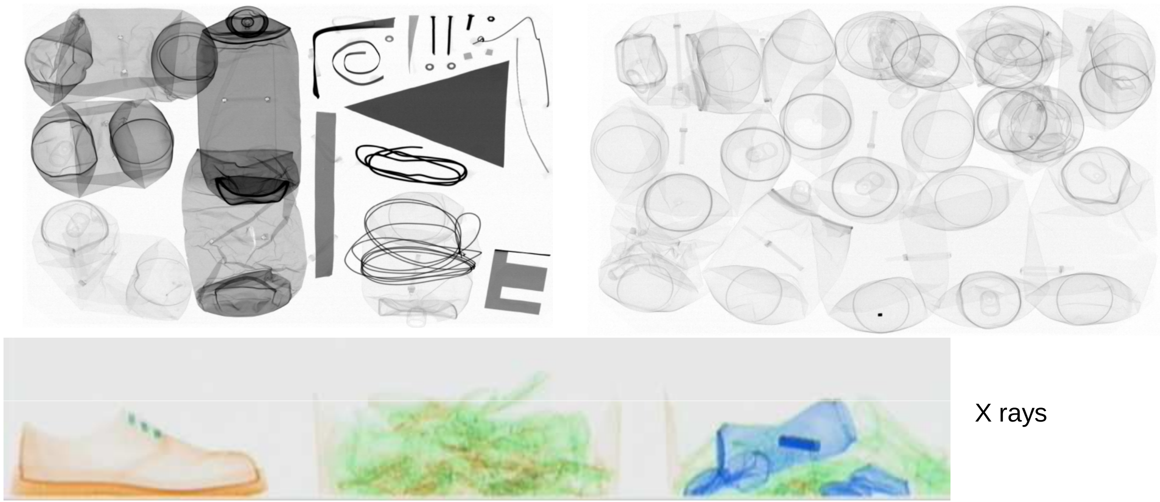
- more than 80% (90%) of information is acquired by human eyes – vision system is potentially rich source of information,
- the present state of development of multimedia technologies,
- the increasing of hardware availability, lower prices of the components, increasing computing efficiency, the progress in development of algorithms for image analysis,
- the growing spectrum of potential and real applications.

Image and spectrum of electromagnetic waves



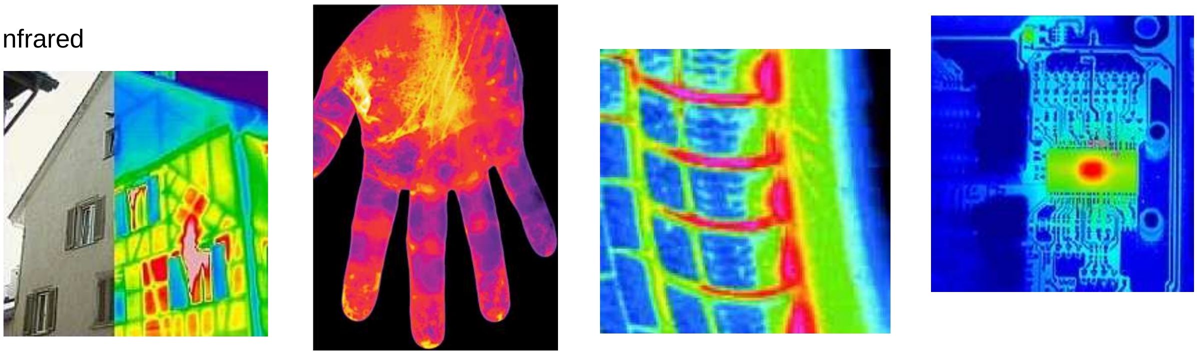
- Gamma rays spectrum – imaging in nuclear medicine,
- X rays – Roentgen images (medicine, inspection, security), astronomy,
- Ultraviolet – lithography, biology (fluorescent microscopes), quality control in the industry,
- Infrared - thermography and thermal imaging, detection of different plastic materials,
- Microwaves - images created on the basis of data from the radar,
- The range of radio waves - magnetic resonance imaging.

Examples of images from different spectral ranges



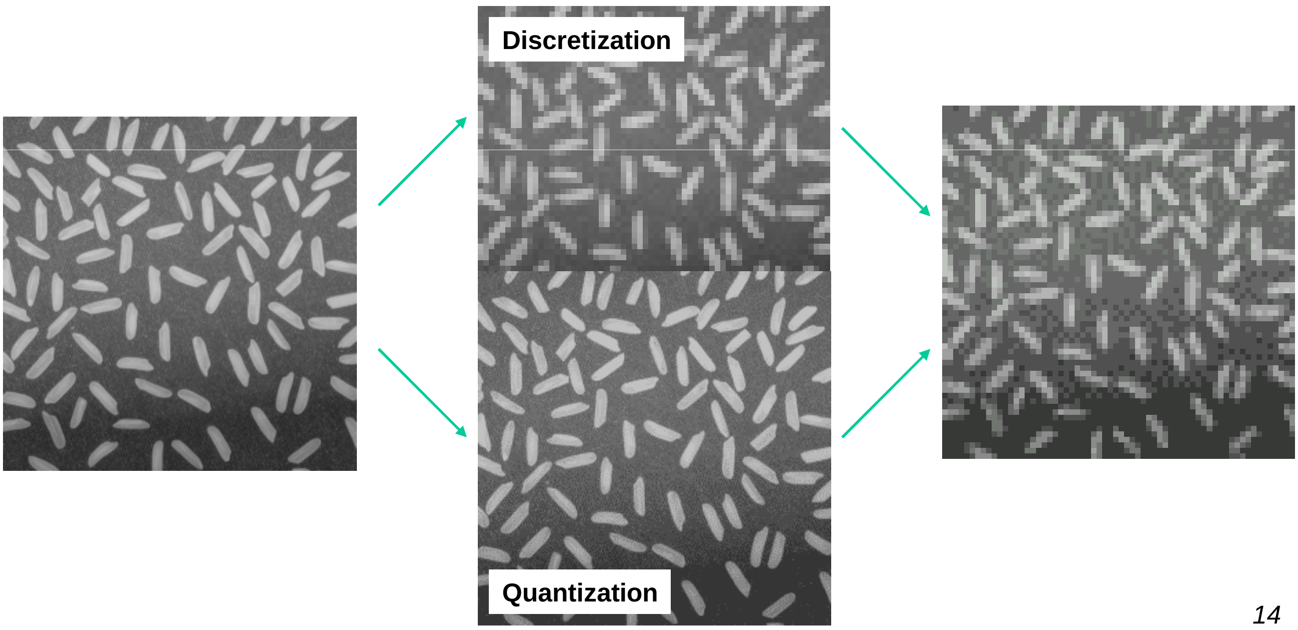
X rays

Infrared

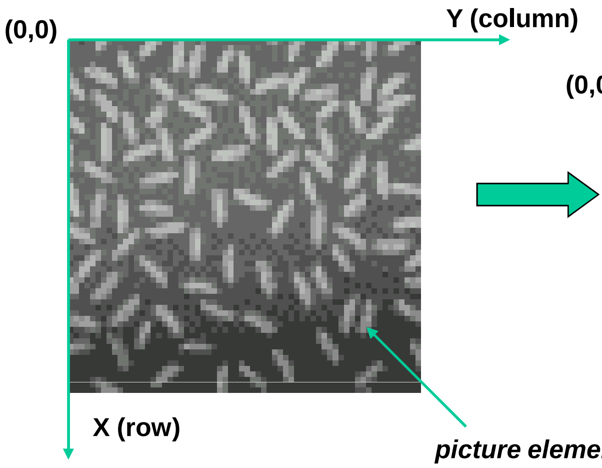


Digital image

- Image analysis by a computer system requires the conversion from analog to digital form - this is done by discretization and quantization of the image in the camera:
  - Discretization of the image is performed by two-dimensional sampling in specific places of the plane of camera matrix sensor (usually in the nodes of a rectangular grid),
  - The quantization consists in dividing a continuous range of brightness into parts and assigning discrete values which representing the individual ranges.



Digital image as a matrix



(0,0)

20	19	18	54	112
18	22	21	65	98
17	16	23	45	88
19	15	22	34	65
21	20	25	31	45

• • •

imtool

- Digital image – two dimensional matrix (M,N) with M rows and N columns, each element is non-negative and can take finite number of values,
- The image function f(x,y)=0,1,...,L-1, where x=0,1,...,M-1, y=0,1,...,N-1, L – specifies the number of gray levels (e.g. L=256).

Basic types of images

- Gray scale images (monochrome images), typically the number of gray level L=256, each pixel is represented by 1 byte (8 bits, 2^8=256).
- Binary images L=2, the pixels can take values 0 or 1, f(x,y)=0;1, each pixel can be represented by 1 bit (this images are used in binarization process).
- Color images – for RGB space color model f(x,y)=R(x,y),G(x,y),B(x,y); typically each component of the pixel has 8 bits (true color images – 24bit) what gives 2^{24}=16777216 different colors.

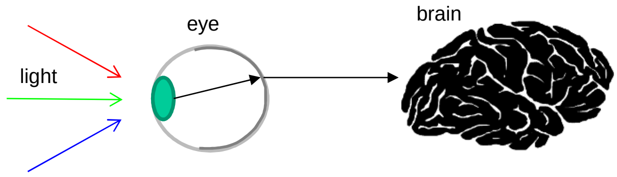
Red

Green

Blue

Human visual perception

Human eye



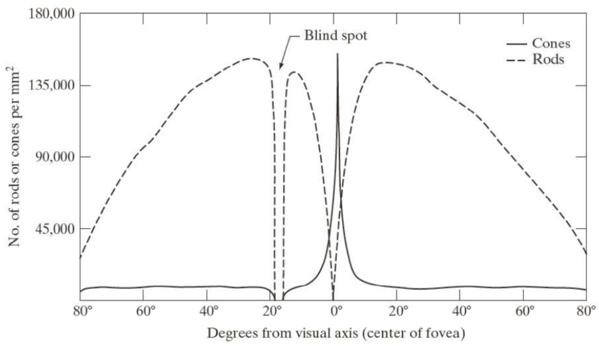
Human eye – can perceive very narrow range of electromagnetic spectrum (wavelengths) which is called visible spectrum. The range of wavelengths is approximately from 350 nm to 780 nm. The colors sensation depends on wavelength of the light and the spectral combinations.

The light in the eye is processed by receptors distributed on surface of the retina. There are two types of receptors, cones and rodes:

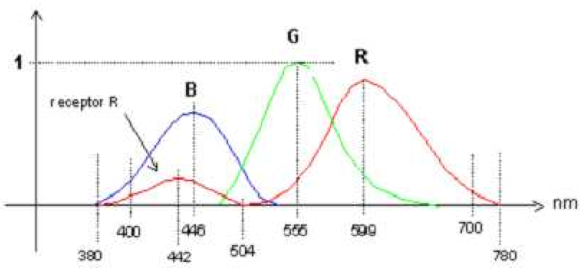
- the cones are located primarily in the central portion of retina (called the fovea) and are responsible for color perception (cone vision is called photopic or bright-light vision), the number of cones is between 6 and 7 milion,
- the rodes are distibuted over the retinal surface and the number of rods is around 130 milion, they are not involved in color vision and are sensitive to low levels of illumination (rods vision is called scotopic or dim-light vision).

Human visual perception

Distribution of rods and cones in the retina



- the area with absence of receptors (called blind spot) is the region of emergence of the optic nerve from the eye,
- the cones are responsible for the perception of the three color components with peak sensitivity at red, green and blue light (note to overlap receiving bands - the same the impression may arise as a result of various configuration of the wavelengths).



Color models

Color vision

The perception of color is most often described by three terms:

- hue (color),
- saturation,
- brightness (luminance).

Hue refers to color names like red, green, yellow etc. and determines the feeling connected with specific wave length from visible spectrum.

Saturation describes how far a hue is from gray level of the same intensity. This means "mixing with white color”, e.g. pure red is a highly saturated in contrast with pink (generally unsaturated colors contains more white light than saturated ones).

Brightness describes the quantity of light stream as achromatic intensity of light emitted or reflected by object.

- Acquisition, processing, displaying or printing color images on different devices, comparison of colors require the ability to quantitative description of colors (mathematical model is needed).
- The basis of the different descriptions of the color space is a RGB theory, according to which the signals from three kinds of cones are responsible for the perception of three RGB components and form a broad, overlapping bands of visible spectrum.

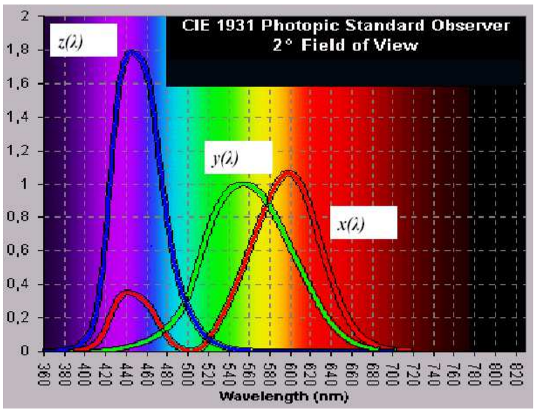
Color models

Two groups of color models

1. Device independent models:
   - CIE XYZ, CIE xy, CIE uvL, CIELab,
   - HLS, HSI, HSV, HSB (user models).
2. Device dependent models:
   - RGB,
   - CMY, CMYK,
   - YUV, YIQ.

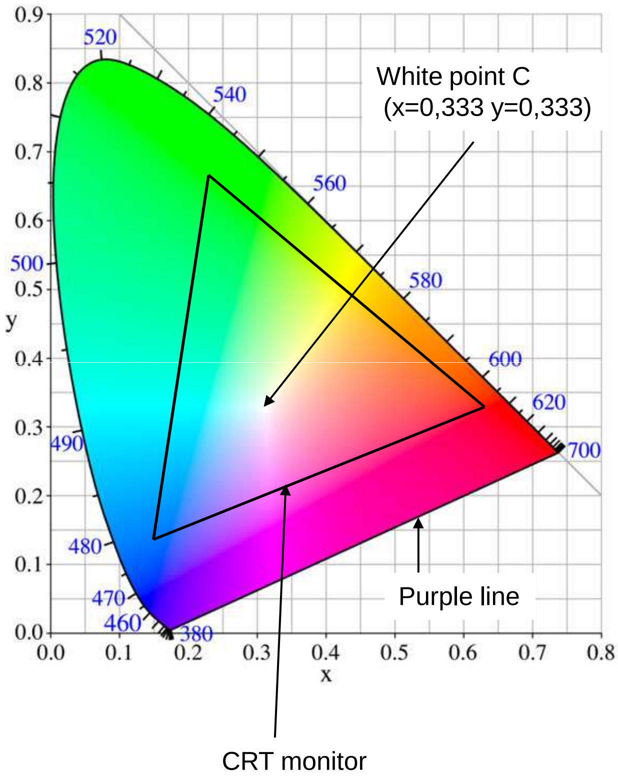
Chromaticity diagram and CIE models

Chromaticity diagram was introduced in 1931 by international committee called the CIE (Commission Internationale de l’ Eclairage). CIE XYZ model is defined by three coordinates XYZ. In this model the light with any hue can be described by three non-negative components.



Color models

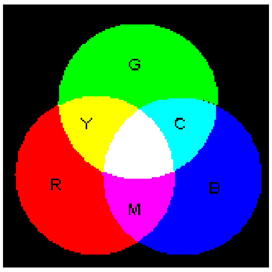
- Chromaticity diagram defines the colors regardless of their luminance. All pure colors (maximum saturated) are located on the curved edge of the diagram area.
- All visible colors can be represented with coefficients x,y>0. The values of the individual R, G, B colors may also take the negative values, which is not possible to display on the monitor. By appropriate selection of primary colors one can affect the area of color displayed.
- The diagram allows to name the colors, specify manner of color mixing and comparison, allows to define and compare the so-called gamuts (subsets of color space) and is the basis for other models.
- The disadvantage of the CIE xy - it is not perceptually uniform, vector operations on the chromaticity diagram are not consistent with human feeling.



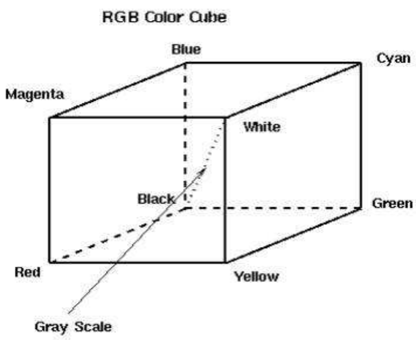
Color models

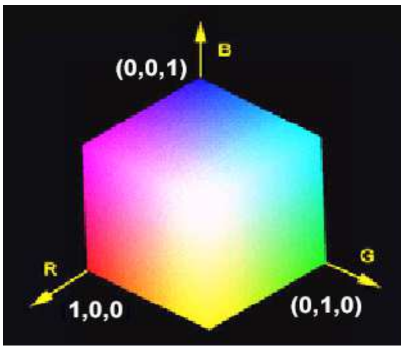
RGB color space – additive color synthesis

- RGB model is directly derived from the RGB theory and is used to generate the image and display on monitors, to represent images in computer memory (this model is not intuitive for determining the hue).
- This model is presented in the form of a unit cube span on the RGB axes.
- Each point inside the color cube is represented by a vector $[R\ G\ B]^T$, where the RGB components can take values from 0 to 1.



Mixing of light





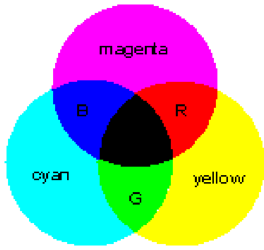
Color models

CMY Model – subtractive color synthesis

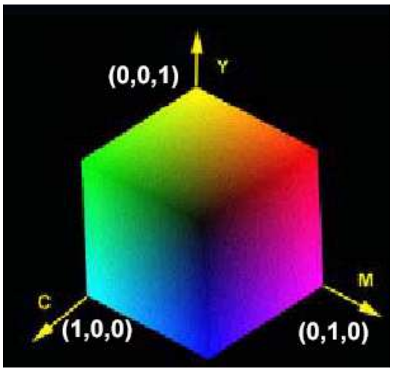
- CMY model is used in the printing industry, printers, plotters or devices that do not have an active source of light (colors are perceived as stream of white light reflected from the surface after "absorption of colors" by the surface – subtractive process).
- Three primary colors: Cyan, Magenta, Yellow, which selectively absorb components of falling white light. RGB to CMY transformation:

$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

where $[1\ 1\ 1]^T$ represents black in the CMY model.



Mixing the pigments



Color models

CMYK model

- CMYK model is created by adding to the three primary colors CMY black color component (blac**K**) - the purpose is to obtain pure black color and higher contrast during printing.
- Conversion from CMY to CMYK model.

$$\begin{bmatrix} C \\ M \\ Y \\ K \end{bmatrix} = \begin{bmatrix} c \\ m \\ y \\ k \end{bmatrix} - \begin{bmatrix} k \\ k \\ k \\ 0 \end{bmatrix}, \qquad k = \min\{c, m, y\}$$

Color models

YUV and YIQ models

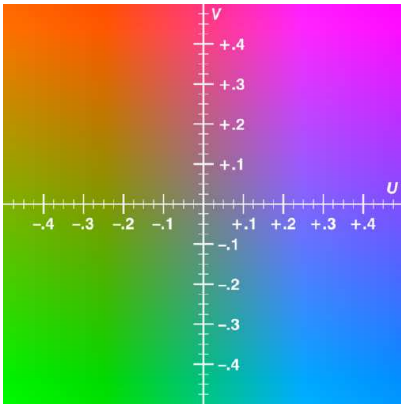
- These color models come from analog television, YUV from the European system PAL, YIQ from U.S. standard NTSC. Both models are linear transformation of the RGB model and was created as a result of research on the optimization of the transmission of television signals.
- Y component (luminance) in both models is the same and has the same function as the CIE XYZ model, it carries information about the brightness of image.

$$Y = 0{,}299R + 0{,}587G + 0{,}114B$$

- The two other components representing chrominance signals of the image and describe hue differentially coded.

PAL: $U = 0{,}493(B - Y)$
$V = 0{,}877(R - Y)$

NTSC: $I = 0{,}740(R - Y) - 0{,}270(B - Y)$
$Q = 0{,}480(R - Y) + 0{,}410(B - Y)$



Color models

- Transformation from RGB to YUV model:

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0{,}299 & 0{,}587 & 0{,}114 \\ -0{,}147 & -0{,}289 & 0{,}437 \\ 0{,}615 & -0{,}515 & -0{,}100 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

- Transformation from RGB to YIQ

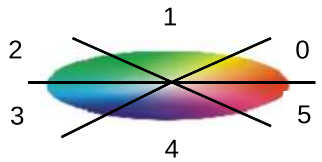
$$\begin{bmatrix} Y \\ I \\ Q \end{bmatrix} = \begin{bmatrix} 0{,}299 & 0{,}587 & 0{,}114 \\ 0{,}596 & -0{,}275 & -0{,}321 \\ 0{,}212 & -0{,}528 & 0{,}311 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

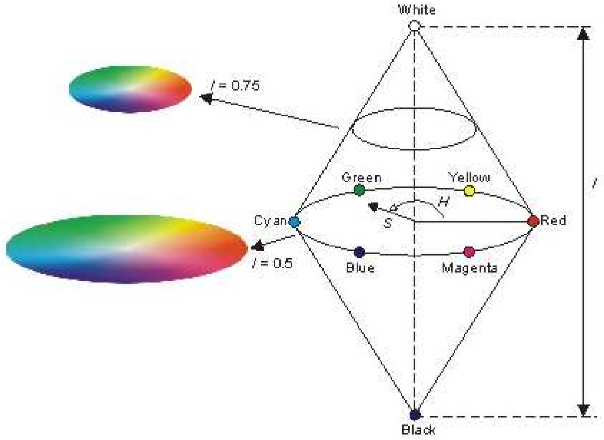
- In accordance with current standards, the luminance value typically should be coded with 8 bits, while the chrominance signals using four bits. This is due to the fact that the human eye is more sensitive to changes in luminance than to incorrect color reproduction.

Color models

HLS and HSI models

- These models allow to select and search for colors in more intuitive way. They allow to specify colors in a manner which refers to the perception and naming of color by the human.
- The color is described by a single Hue component representing the spectral hue of the light wave. General assignment of frequencies of the visible spectrum resulting from division of full angle (360 degrees) into three parts of 120 degrees (Newton's color circle). The center of the red color corresponds to the angle of 0 or 360 degrees, green to 120, and blue to 240 degrees.
- Saturation component S represents color saturation (range typically 0 to 1). For S = 0, the color component H is undetermined.
- L component of the HLS model (range typically 0 to 1) represents the average lightness of the color.
- In the case of HSI model I component (range typically 0 to 1) describes the intensity of color.

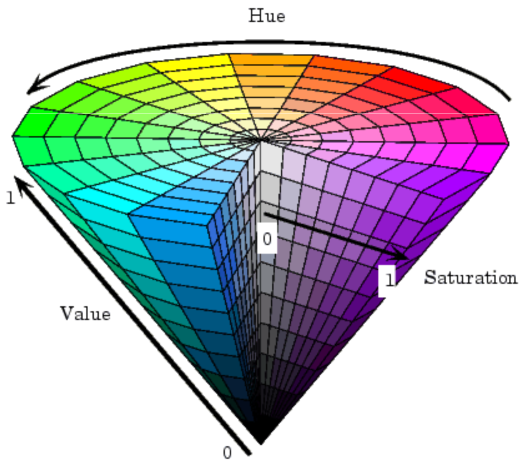




Color models

HSV and HSB models

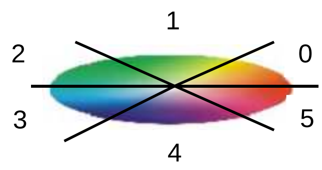
- Models similar to HLS and HSI, also allow to specify colors in a manner which refers to the perception and naming of colors by human.
- Color component is defined analogously to HLS and HSI model and is described by a single Hue component. Saturation component similarly represents saturation of color. For S = 0, the color component H is also undetermined.
- Component Value or Brightness represents the white level from which the color is derived.



Color models

Transformation from RGB to HSV (HSB)

1. Sort the (r,g,b) elements ascending and assign them in sequence m0, m1, m2
2. Component V=m2
3. Component S=(m2-m0)/m2
4. From m0 and m2 determine section number n in Newton's color circle
5. Calculate F:
   - F=(m1-m0)/(m2-m0) for n={0,2,4} or
   - F=(m2-m1)/(m2-m0) for n={1,3,5}
6. Calculate H=n*60+F*60



Inverse transformation from HSV (HSB) to RGB

1. Determine m2 from V m2=V
2. Calculate m0=V(1-S)
3. Determine section number n=(H mod 60)
4. Calculate F=(H-n*60)/60
5. Calculate
   - m1=m0+(m2-m0)*F for n={0,2,4} or
   - m1=m2-(m2-m0)*F for n={1,3,5}
6. Assign m0, m1, m2 to (r,g,b) according to section number n