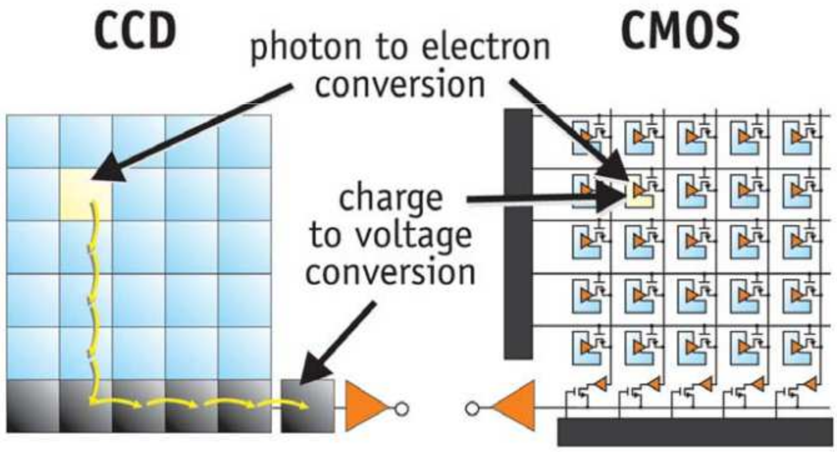
Components of machine vision systems

Cameras

- CCD or CMOS matrix sensor – main element of the camera, which process luminous flux into electrical signals (invented: late 60, early 70)



Components of machine vision systems

CCD (Charged Coupled Device)

- Smaller susceptibility to noise, higher sensitivity (lower dark noise), negative property of charge losing during charge propagation,
- Progressive scan or interlaced, global shutter,
- CCD sensor allows readout of AOI (Area Of Interest), but it is connected with the necessity to read the contents of entire lines (columns), the omission of lines during acquisition allows to increase readout speed.

Blooming effect

CMOS (Complementary Metal Oxide Semiconductor)

- Cheaper technology, lower power consumption, easy access to any area of the matrix, the ability to integrate sensor processing modules in one chip (reducing the size of the module),
- Progressive scan,
- Global shutter as in the CCD or rolling shutter,
- CMOS sensors can read from any AOI, the reading is possible in the selected area without having to read the entire contents of the line/column (wider opportunities to increase the speed of acquisition).

Distortion caused by a rolling shutter

sCMOS (Scientific CMOS) and HDR CMOS (High Dynamic Range CMOS)

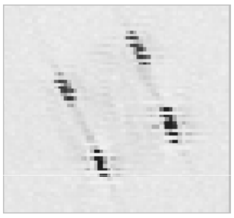
- Sensors for scientific purposes (medicine and astronomy),
- Very low noise level, high dynamic range from single exposure, high sensitivity.

Components of machine vision systems

- Analog cameras and digital cameras

The division to analog and digital results from the manner of the video signal transmission (type of the camera video output) in analog or digital form (choice of a particular standard is crusial to the performance and capabilities of a vision system)

– Analog PAL and NTSC cameras



Interlaced scanning

- resolution up to hundreds of TV lines,
- PAL standard 625 lines and 25fps (interlaced scanning, characteristic interlace in the image),
- NTSC standard 525 lines and 30fps (interlaced scanning)
- video output type composite, S-Video or RGB,
- image acquisition card (framegrabber) is required,
- the entire image have to be acquired by the framegrabber (any AOI can be processed after image acquisition in the memory of processing unit),
- easy use of wired and wireless video transmission,
- susceptibility to interference during the video signal transmission.

– Analog HD cameras for CCTV (Closed Circuit TeleVision)

- transmissions standards 960H(700TVL), HDCVI(720p/1080p), HDTVI(720p/1080p), AHD(720p/1080p),
- the video signal is transmitted through the composite coaxial cable.

Components of machine vision systems

– Digital cameras

- resolutions from VGA (0.3 megapixel) to over 10Mpx,
- global shutter (CCD and CMOS), rolling shutter (CMOS),
- standard digital interfaces or dedicated e.g. CameraLink,
- acquisition speed from a few up to hundreds of images per second or even more,
- no need for conversion to analog and then to digital form in the processing system (less interferences compared to analog cameras),
- direct access to the RAW data type (advantage and disadvantage),
- limiting the length of connection cables resulting from interfaces specification.

Interface	CameraLink	FireWire 1394a(b)	USB 2.0	GigEVision	CoaXPress
Throughput	5,44Gb/s	400 (800) Mb/s	480Mb/s	1Gb/s	6,25Gb/s
Length of cable	10m	4,5 (100) m	5m	100m	40m
Number of cameras	1	Up to 63	Up to 127	Unlimited	Dependent on the card
Power Supply	External	By the interface External	By the interface External	External	By the interface External
System costs	High	Low (medium)	Low	Low or medium	High

Components of machine vision systems

– CameraLink interface (year 2000)
  - for applications that require very high performance, full control of the camera triggering and acquisition, minimum delays in the system,
  - dedicated framegrabber card with CameraLink interface is required,
  - three operating modes: Base (2.04 Gb/s), Medium (4.08 Gb/s) and Full (5.44 Gb/s),
  - Medium and Full mode requires two independent cables and inputs in framegrabber card compatible with the full interface specification,
  - the number of interface lines 2x26,
  - external power supply for the camera is required.

– CameraLink interface HS (year 2012)
  - Packet data transmission, basic effective bandwidth 300MB / s (max. Up to 8400MB / s) per cable (up to eight cables)
  - Copper (up to 15m) and fiber optic (up to 5km) cables, return channel and GPIO available.

– IEEE-1394a FireWire interface (400Mb/s)
  - small delays in the system and time determinism,
  - possibility to use standard FireWire interfaces in computer systems,
  - possibility to easy camera changing due to DCAM industry standard,
  - cameras can be easy powered by the FireWire interface.

– IEEE-1394b FireWire interface (800Mb/s)
  - backward compatibility with version 1394a,
  - the necessity for using dedicated interface cards with inputs 1394b (9 wires).

Components of machine vision systems

– USB 2.0 (480Mb/s)
  - wide availability and the universality of the interface -> low cost,
  - performance similar to FireWire,
  - cameras can be powered via the USB interface,
  - there are no one industry standard that defines communication with cameras,
  - possible problems with delays in the system,
  - USB 3.0 (up to 5Gb/s, 5m) - a relatively inexpensive alternative to high-performance applications.

– USB 3.0, 3.1, 3.2
  - established USB3 Vision standard in 2013, a cheap alternative to relatively efficient applications,
  - interface speeds 5Gb/s (effectively over 400MB/s), 10Gb/s and 20Gb/s,
  - cable length up to 5m (power supply), optical fiber up to 100m.

– GigE Vision 1Gb/s (year 2006)
  - the cameras use a standard gigabit ethernet infrastructure, it is easy to connect multiple cameras to the ethernet network which gives low cost of system (theoretically),
  - to achieve full performance of the cameras all ethernet devices have to support transmission of large packets called Jumbo Frames,
  - in direct connection camera to computer relatively high performance with low latency,
  - optical fiber data transmission possibility,
  - in 2011, the version 2.0 was expanded to include 10Gb/s transfer support.

Components of machine vision systems

– CoaXPress interface
  - one of the newest interface for transmitting digital video in vision systems (2011), uses coaxial cable,
  - basic data rate of 6.25 Gb/s, the possibility of combining several channels to increase the transfer from the camera (e.g., 4 channels - 25GB/s)
  - simultaneous control data sending to the camera with 20.8Mb/s,
  - power supply for the camera by the same cable (24V up to 13W per cable),
  - the possibility of reducing the speed and extend the cable length up to 140m,
  - the number of cameras depends on the number of input in the acquisition card (it is possible to send video signals from multiple cameras by one channel).

– IP cameras
  - they use typically 100Mb/s ethernet or WiFi connections, there is ability to power through twisted pair cable (PoE),
  - high latency, typically used lossy image compression,
  - the simplicity of integration, the possibility of wireless transmission,
  - the possibility to use in remote inspection tasks, navigation by human, etc.

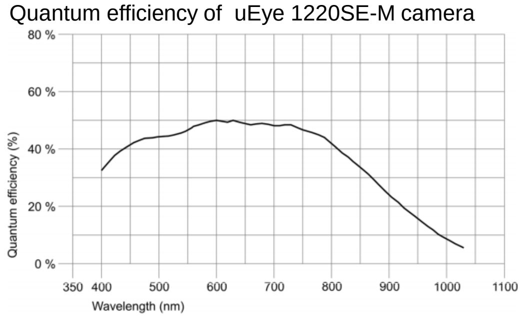
Components of machine vision systems

– Color and monochrome cameras

- monochrome camera

G	G	G	G	G	G	G	G	G
G	G	G	G	G	G	G	G	G
G	G	G	G	G	G	G	G	G
G	G	G	G	G	G	G	G	G
G	G	G	G	G	G	G	G	G
G	G	G	G	G	G	G	G	G

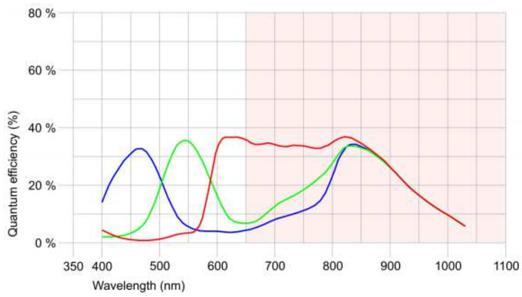
Quantum efficiency of uEye 1220SE-M camera



- color camera with one sensor (with Bayer mosaic filter)

G	B	G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G	R	G
G	B	G	B	G	B	G	B	G	B	G	B
R	G	R	G	R	G	R	G	R	G	R	G

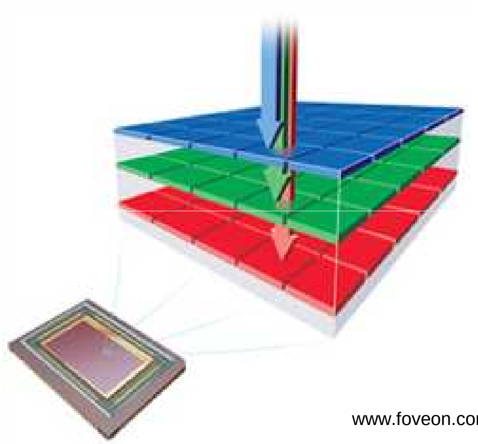
Quantum efficiency of uEye 1220SE-C camera



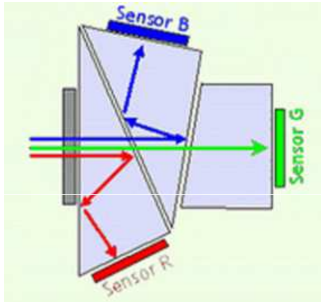
Components of machine vision systems

- Cameras with 3 sensor matrices for RGB components

  Each matrix has a filter which transmits only one of the RGB basic components
- Camera with FOVEON X3 sensor



www.foveon.com



- Line scan cameras (monochrome or color)

R	G	B	R	G	B	R	G	B	R	G	B

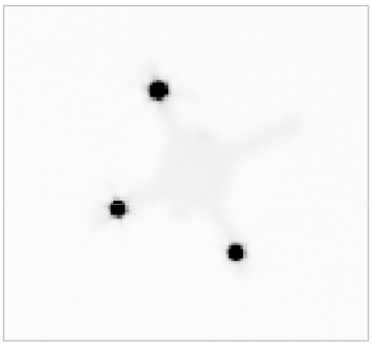
G	G	G	G	G	G	G	G	G	G	G	G
R	G	B	R	G	B	R	G	B	R	G	B

R	R	R	R	R	R	R	R	R	R	R	R
G	G	G	G	G	G	G	G	G	G	G	G
B	B	B	B	B	B	B	B	B	B	B	B

Components of machine vision systems

– Exposure time (shutter speed)

- According to the standards exposure time is: 1/1000, 1/500,1/250, 1/125, 1/60, 1/30, 1/15, 1/8, 1/4, 1/2 and 1 second.



Sharp image with static object

Fast rotating object with too long exposure time

Components of machine vision systems

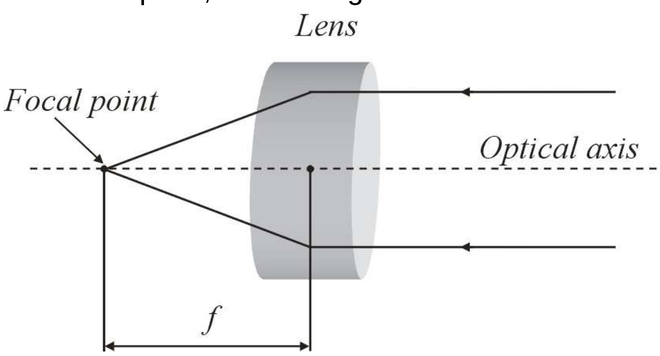
– Size of the camera sensor
  - Currently common sensors are marked by size 1/4”, 1/3”, 1/2”, 1/1.8”, 2/3”, 1, 1.2” (for special applications also larger). Typical sensor sizes used in machine vision systems varies from 1/3” to 1”.
  - Size in inches does not mean direct physical dimensions of the sensor matrix, and refers historically to the outer size of tubes (in inches) used in analog television cameras.
  - Larger matrices have usually larger dimensions of the pixels, higher sensitivity, lower noise content and higher image quality (higher costs of sensors and lenses).
  - Sensor size in combination with the lens determines the field of view of the camera.

Sensor	1/4”	1/3”	1/2”	1/1.8”	2/3”	1”	1.2”
Dimensions [mm]	2,7x3,6	3,6x4,8	4,8x6,4	5,4x7,2	6,6x8,8	9,6x12,8	15,2x15,2
Diagonal [mm]	4,5	6	8	9	11	16	21,5

Components of machine vision systems

The optical system of the camera

- The purpose of the optical system (lens) is the projection of the observed scene to the surface of a photosensitive sensor matrix of the camera. The lens have to ensure the correct mapping of elements of the scene and required field of view of the camera. Usually, the lens is selected for the camera, according to the system requirements. In machine vision less common are lenses integrated with the camera.
- Parameters of the lenses
  – focal length *f* – expressed in millimeters and defining the distance from optical center of the lens to the focal point, in which light beams are focused.



Components of machine vision systems

– F number (the aperture of the lens) (f/# or N) – means the degree of aperture and is defined as the ratio of the focal length f to diameter D of the entrance pupil of the lens

According to standards, the aperture values on the lenses correspond to the values resulting from $\sqrt{2}^n$ where $n = 0; 1; 2; 3 \ldots$
what gives a typical series of values 1; 1,4; 2; 2,8; 4; 5,6; 8;...

Amount of transmitted light depending on the aperture

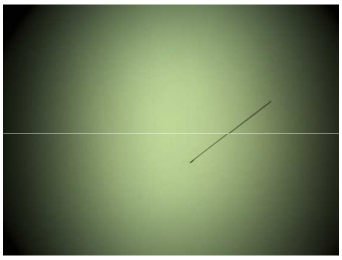
F	1,0	1,4	2	2,8	4,0	5,6	8,0	16
Amount of transmitted light	100%	50%	25%	12,5%	6,25%	3,13%	1,6%	0,8%

The smallest aperture value indicated on the lens (doesn’t have to be in a aperture series) means the maximum entrance pupil and determines the brightness of the lens, the designation 'c' specifies the complete closure of the aperture.

Components of machine vision systems

– depth of field - the distance range in which objects are mapped sharply. Depth of field depend on the focal length and aperture of the lens. Reducing the focal length and closing aperture increase the depth of field. In the case of lenses used in machine vision, an important parameter is the minimum distance to the object which allows to achieve sharp images.

– lens size - expressed in inches, is the maximum size of the matrix sensor which can work correctly with the lens (the use of larger matrix causes so-called vignetting in the image). The lens of a given size can always be used for cameras with smaller sensors. In some cases it is useful, as it allows to reduce the geometric distortion introduced by the optics of the lens (typically geometric distortions increase with distance from the optical axis of the lens). The smaller size of the matrix sensor with the same lens reduce the field of view.



– angle of view - depends on the focal length of the lens and the size of the camera sensor. For given camera, lens with a short focal length provides wide angle of view, contrary a long focal lenght gives narrow angle. Manufacturers usually give information about angle of view for the corresponding sensor size.

Components of machine vision systems

- Types of lens mount
  - C and CS, commonly used, have the same flange with thread of screw, differs only in the plane of the lens mount distance from the plane of the sensor in the camera. For C mount lenses the distance is 17,526 mm, while for the CS 12.526 mm. This means that the lenses with C-mount can be used with CS-mount cameras by the spacer (with 5 mm spacer ring).
  - S (microVideo) is used in miniature cameras (board level cameras).
  - F, T, M for cameras with big sensors matrices.
  - there are special adapters that allow the use of C-mount lenses for cameras with F-mount and other.
- Lenses with a fixed focal length and variable focal length (manual or motozoom)
- Lenses with Auto Iris and Auto Focus




Components of machine vision systems

- Types of lenses for machine vision and measurement vision systems
  - megapixel lenses - usually used for cameras with high-resolution sensor, characterized by smaller geometric distortion (spherical aberration and distortion) due to less deformation of the light wave passing through the lens, which allows for acquiring images with sharp details.
  - aspherical lenses - the type of lens is characterized by high brightness (larger aperture), through the use of aspherical lenses (instead of the traditional spherical lens profile), which transmit light better especially at the edges of the lens, corrects distortion and increasing sharpness in the outer parts of the image. Aspherical lenses are commonly used in the megapixel lenses.
  - telecentric lenses - are used in precision measurement systems. These lenses do not have the effect of perspective and angular distortion of the image (parallax error). In standard lenses the same object is seen as greater when it is closer to the lens and smaller when it is farther. They are characterized by a relatively small field of view and very shallow depth of field.


Components of machine vision systems

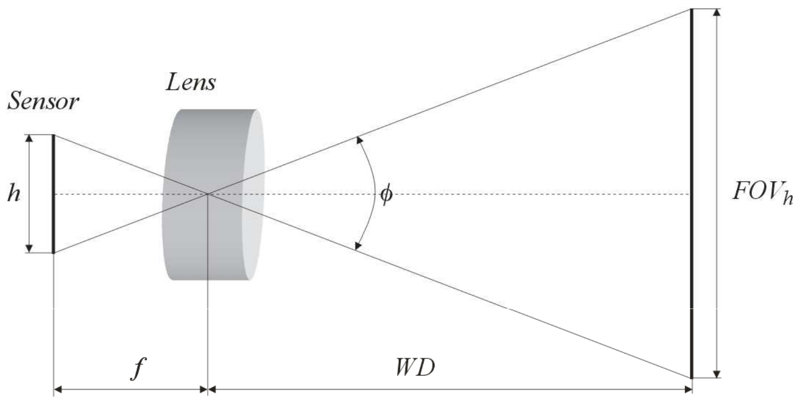
- Fish-eye lenses, and the camera with a standard lens and parabolic or similar mirror for omnidirectional camera






Components of machine vision systems

- The geometry of the optical system to determine the focal length



– The focal length is usually estimated based on the desired field of view FOV for a given distance from the camera, the maximum size of the observed object or viewing angle. Taking the WD as camera distance from the object, FOV_h and FOV_v accordingly as the width and height of the field of view and h , v for the width and the height of the image sensor, the focal length f can be calculated from the geometrical relationships

$$f_h = \frac{h}{FOV_h} WD \qquad \text{in horizontal direction}$$
$$f_v = \frac{v}{FOV_v} WD \qquad \text{in vertical direction}$$

Components of machine vision systems

Calculations in horizontal and vertical direction give typically different results. In order to properly acquire image with the whole object or desired field of view a shorter focal length should be used.

– Calculation of the focal length for a given angle of view ϕ, based on the trigonometric relationship

$$f_h = \frac{h}{2\tan\frac{\phi}{2}} \qquad \text{in horizontal direction}$$

$$f_v = \frac{v}{2\tan\frac{\phi}{2}} \qquad \text{in vertical direction}$$

– Resolution of the vision system

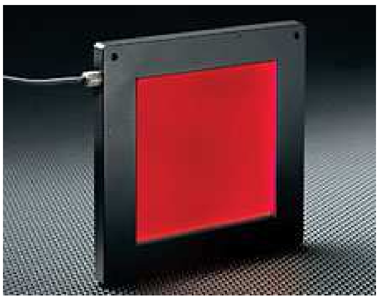
Resolution R_h [lp/mm] is determined on the basis of the number of pairs of pixels (lp) in the line and the corresponding width of the field of view FOV_h

$$R_h = \frac{number\ of\ pixels}{2FOV_h}$$

Components of machine vision systems

Lights and illuminators for machine vision systems

- The sensitivity of color cameras typically is less than monochrome cameras
- Selection of the lens with suitable brightness according to lighting conditions
- Light sources: LED, incandescent, fluorescent, laser

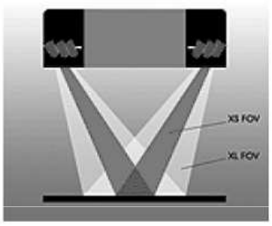





Components of machine vision systems

– Ring type illuminators with a hole for the lens

It is used for general illumination of the object, without emphasizing any features of the object.



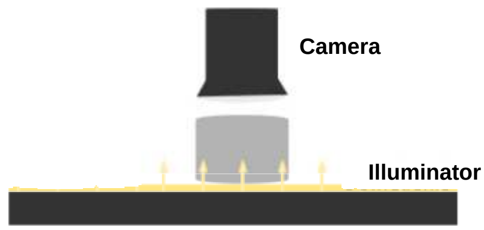
– Dark field ring illuminators

The LEDs are mounted at some angle. This allows to highlight the edges of the object while darkening uniform parts of the image.

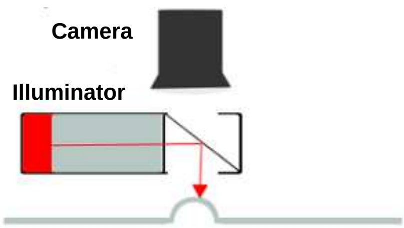
Components of machine vision systems

– Backlight illuminators

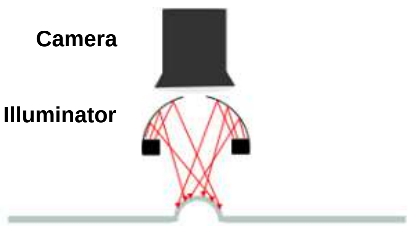
Illuminator is mounted from the bottom (or back) of the object, the image has a bright background and blackened blob in the shape of the object, most often used to detect objects in the observed field of view.



– Diffuse light illuminators



Axial diffuse light



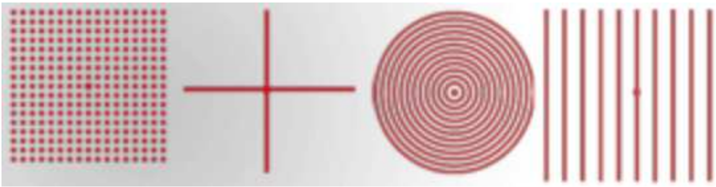
diffuse light

Components of machine vision systems

– Structured light illuminators

Source of light - lasers or diodes in visible or infrared spectrum.

The aim is to obtain a specific structure of light on the object/scene that facilitates measurements on the image and allows to acquire information in 3D space (used in RGB-D cameras, 3D scanners).



Laser Components

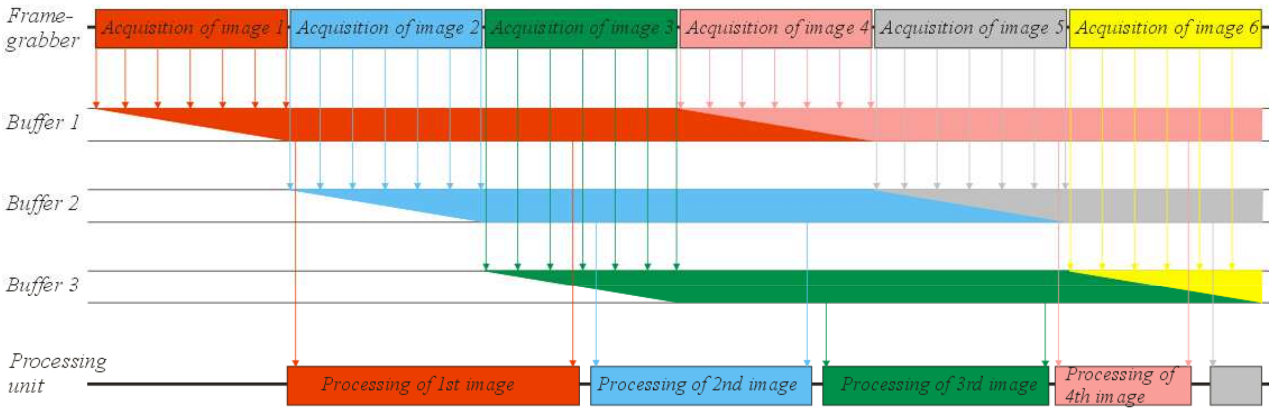
Components of machine vision systems

Image acquisition, hardware and software

- Analog cameras - framegrabber card for a computer system with analog inputs (composite, S-Video, RGB).
- Digital cameras – dedicated digital interface cards (CameraLink, CoaXPress) or standard digital interfaces (USB, FireWire) or network (Ethernet 1Gb/s).
- Image acquisition and store in memory is done using libraries usually attached to framegrabber cards or cameras (SDK) - MIL-Lite (Matrox), MultiCam (Euresys), FirePackage (AVT), PylonDriver (Basler) or universal libraries for image acquisition and processing.
- Choosing the adequate color space for the acquisition of color images according to image processing algorithms (RGB, YUV, RAW)
  - Analog cameras - the number and type of available formats depend on the framgrabber card
  - Digital cameras - number and type of available formats depends only on the camera type
- Application of the buffering techniques
  - It allows simultaneous image acquisition and processing
  - Typically, a double or triple buffering technique can be used

Components of machine vision systems

– Acquisition and processing using three buffers

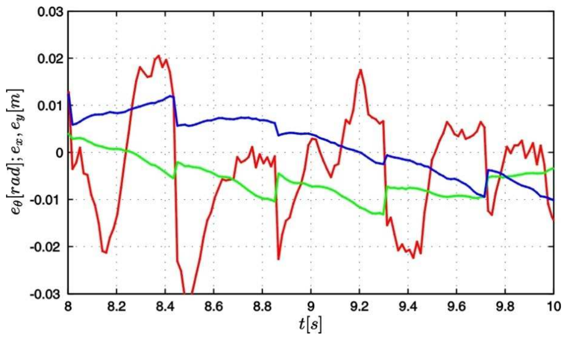


– The application of a vision system for control purpose requires constant sampling time which can be achieved by synchronizing control loop by the image acquisition process (required condition: the time of image processing must be shorter than the time of image acquisition)

Components of machine vision systems

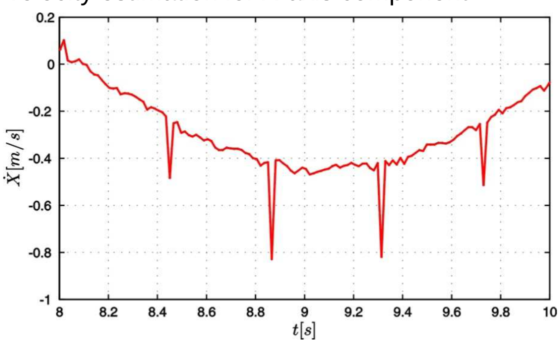
– Synchronization in the control system

- Error signal in trajectory tracking



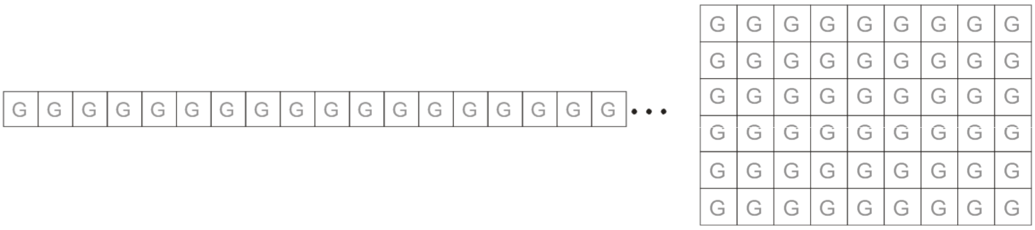
The synchronization has to be done by the vision system!

- The velocity estimation for X-axis component



Components of machine vision systems

– Representation of the image in the memory system
- Image buffer typically is a continuous fragment of system memory, the correct interpretation of image data requires knowledge of the number of rows and columns of the image and structure of the data
- Monochrome images (m rows, n columns)



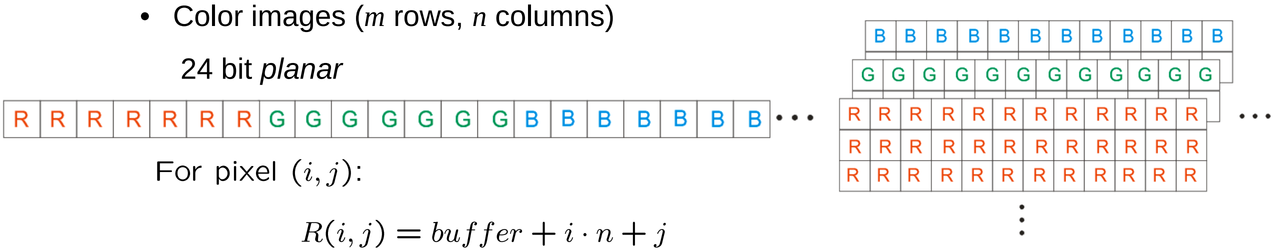
For pixel (i, j):

$$G(i, j) = buffer + i \cdot n + j$$

Components of machine vision systems

– Representation of the image in the memory system
- Color images (m rows, n columns)

24 bit *planar*



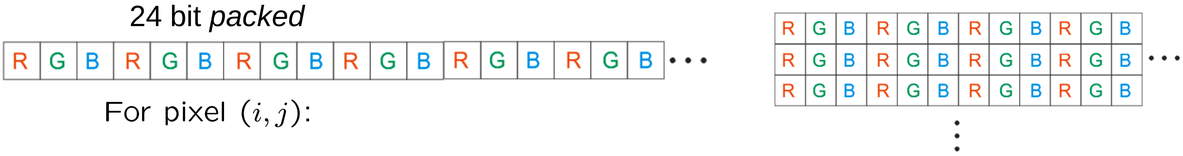
For pixel (i, j):

$$R(i, j) = buffer + i \cdot n + j$$

$$G(i, j) = buffer + m \cdot n + i \cdot n + j$$

$$B(i, j) = buffer + 2m \cdot n + i \cdot n + j$$

24 bit *packed*



For pixel (i, j):

$$R(i, j) = buffer + 3 \cdot i \cdot n + 3 \cdot j$$

$$G(i, j) = buffer + 3 \cdot i \cdot n + 3 \cdot j + 1$$

$$B(i, j) = buffer + 3 \cdot i \cdot n + 3 \cdot j + 2$$

Components of machine vision systems

- Image processing, libraries
  - Commercial
    - MIL – Matrox, eVision – Euresys, CommonVisionBlox, HALCON, VisionLab, RoboRealm, ...
  - OpenCV, ...
  - Rapid prototyping tools
    - Matlab with IAT, IPT, CVT,…
    - LabView with Vision Builder
- Example in Matlab-IAT (Image Acquisition Toolbox)

```
info=imaqhwinfo
info=imaqhwinfo('winvideo')
dev=imaqhwinfo('winvideo',1)
dev.SupportedFormats
v=videoinput('winvideo',1,'I420_640x480')
preview(v)
pause
closepreview(v)
delete(v)
```

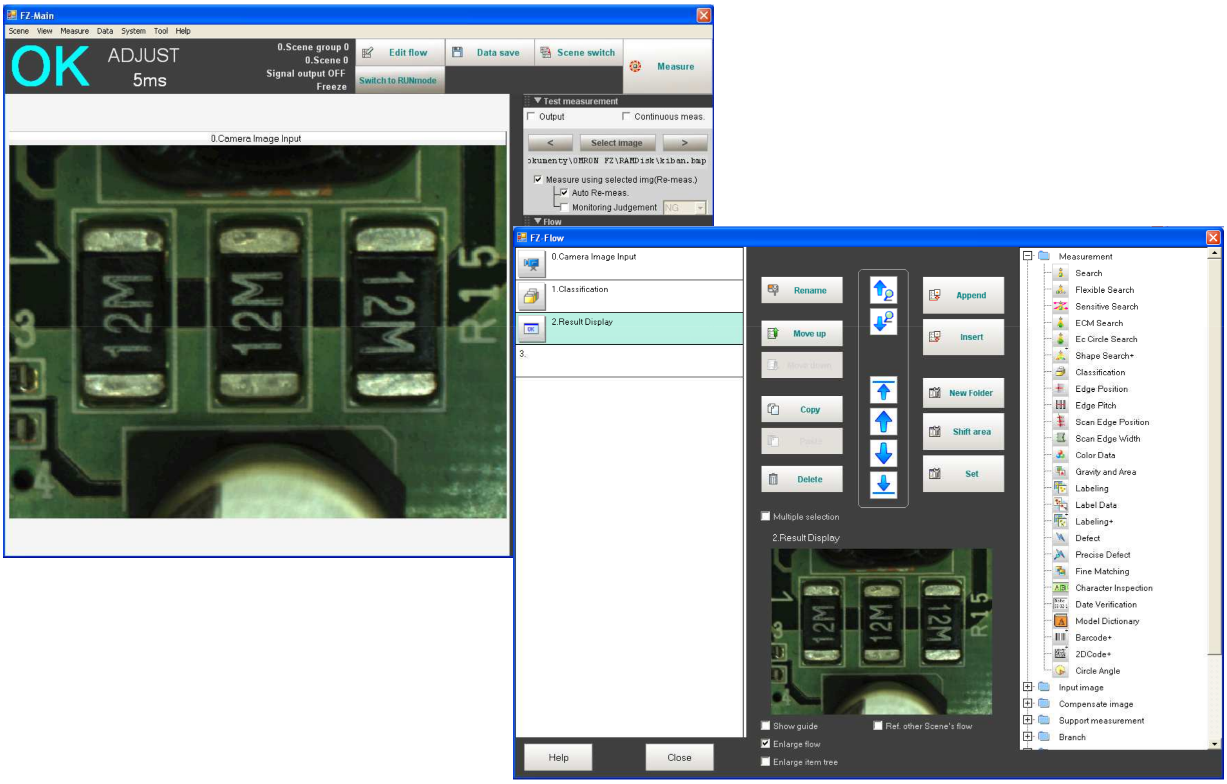

Industrial vision systems and smart cameras

Industrial vision systems and smart cameras

- Omron – vision systems and sensors

Industrial vision systems and smart cameras

- Omron –Xpectia FZ3 simulator



Industrial vision systems and smart cameras

- SICK, Cognex, Matrox, KEYENCE – vision systems and smart cameras

IDS NXT vegas
Vision app-based sensor