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Theory and Applications of Digital Image Processing

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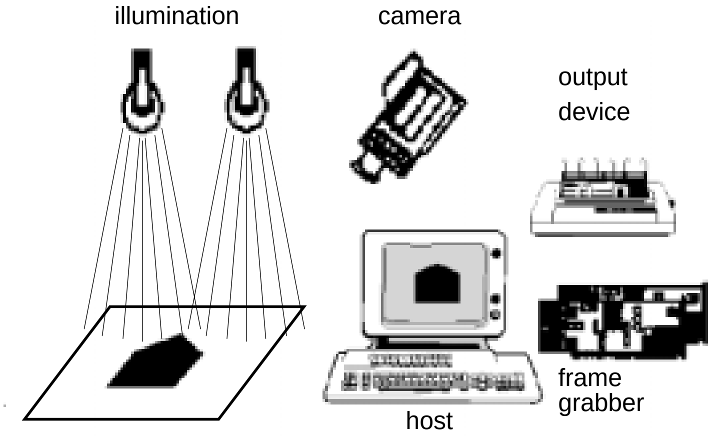
1 The Image Processing System

An image processing system (fig. 1.1) consists of a light source to illuminate the scene, a sensor system (usually a CCD -camera) and an interface between the sensor system and the computer. Among other things, the interface converts analog information into digital data which the computer can understand. This takes place in a special piece of hardware, the frame grabber, which also stores the image. Many types of frame grabber hardware are supplied with special signal processors, so that very calculation-intensive parts of the image processing programs can be run in a time-efficient way. Usually the frame grabber package contains a library of often-used routines which can be linked to the user's program. The results of an image processing run will be transferred to the outside world by one or more I/O interfaces, the screen and the normal output devices like printer, disks etc.



1.1: Components of an image processing system

The classical configuration of image processing hardware is not a stand-alone system but has to be directed by a host computer. However, the newest developments are able to integrate the complete image processing system into the camera.

In this module we will talk about the hardware components of image processing systems. You will receive the basics which will enable you to conceptualize an image processing system along with the knowledge necessary to be able to compare the capability and the compatibility of components offered by different companies You should be familiar with the terminology in the field of personal computers. In addition, some knowledge of algebra is required for part 1.2.3 of this unit.

1.1 Illuminating the Scene

An important aspect of image processing is the proper choice of light source, which has to be appropriate to the system's working environment. A good choice of illumination will allow the image processing system to receive the best image under the circumstances and the number of procedures necessary for image restoration will be minimized. The goal is to optimize the dynamics and the contrast of an image. This means that an object has to be photographed with a maximum number of intensity steps and should, at the same time, have the best possible contrast with its background.

By the choice of the *light source* the features of the radiation (e.g. wavelength, direction of oscillation, spatial intensity distribution), can be selected depending on the requirements of the object's surface (i.e. structure, color, transparency etc.). In any case, however, the aim is to establish a homogenous and temporally constant illumination over the whole area of interest.

Daylight is usually not very well suited to illuminating a scene for image processing because the color and the intensity of the light depend on the time of day, the time of year and the weather conditions. Similarly ill-suited is the uncontrollable light in a production line in a factory hall. Situations where uncontrolled light cannot be avoided, for example in the environment of autonomous moving vehicles, will always provide challenges for the image processing system.

Tungsten light sources are very cheap but not very well suited for image processing, especially if the image readout frequency of the camera is not a multiple of the net frequency (i.e. 50 Hz or 60 Hz). This is often the case with cameras with features other than those required by the video norm, e.g. line cameras. In this case, light frequency and the image readout frequency differ, resulting in undesired interference, which appears as lighter and darker stripes on the screen and which reduces the image quality. Of course, they could be operated with direct current but an additional drawback is a non-uniform illumination field along with the fact that they get very hot.

Fluorescent lamps have a large homogenous illumination field. They can be operated with frequency rectifiers to prevent a modulation of the light intensity and the resulting interference. In addition, they do not get very hot. One possible disadvantage could be the spectral limitation which is provided by the fill, but depending on the application this might even be a desirable feature. Indeed, fluorescent lamps are therefore often used to illuminate scenes for image processing.

Quartz Tungsten Halogen (QTH) lamps do not have the problem with mains frequencies. Like normal tungsten lamps they have a tungsten filament inside, which starts to glow when connected to electricity. However, opposed to normal tungsten lamps, they are filled with a rare gas and a small amount of a halogen, (mostly iodine or bromine compounds). When the lamp is turned on the following thermo- chemical process called *halogen cycle* takes place:

- The tungsten atoms, which are emitted from the hot filament (3300 °C) cool down at some distance to a temperature below 1400 °C. There they chemically react with the halogen - atoms. This chemical compound is gaseous down to a temperature of 250 °C.
- With the thermal current of the halogen gas the compound molecules get close to the hot tungsten filament, where they are divided up into their parts - tungsten and the halogen.
- The tungsten attaches to the filament, the halogen is free for a new repetition of the process.

Because of this eternal rejuvenation of the filament, the temperature of the filament can be much higher than the one of a normal tungsten lamp, and the intensity does not vary much during one period of the alternating current. The result is that halogen lamps are light sources with almost constant light intensity. They are usually not directly applied to the scene, but mainly used as feeding light sources for fiber optical systems.

Using fiber optical systems to illuminate small objects makes it possible to adjust the angular distribution of the light intensity exactly to the requirements of the task. In addition, areas which are hard to access can be illuminated properly. The disadvantages with fiberoptics are the fact that about 40% of the light intensity is lost by scattering and reflection effects and the relatively high price of the lamps.

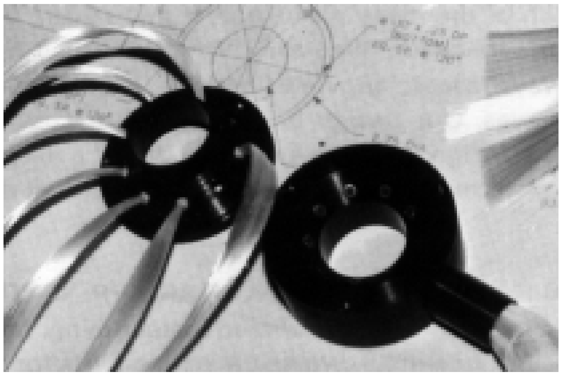
Discharge lamps have very high radiation densities, a temporally constant luminosity and their electromagnetic spectrum shows continuous or discrete lines, depending on the illuminating gas. Certain kinds (flashlights) can be used for stroboscopic illumination. However, they are also relatively expensive.

Light Emitting Diodes(LED's) react instantly and almost without inertia to contol light intensity over a very wide range. This also makes them suitable for stroboscopic applications. Another advantage is their good monochromatic nature which particularly suits them to situations where the chromatic aberration of the camera objective plays a role. Additionally, they are reasonably priced, inexpensive to operate, and they are small and lightweight. Their lifetime of about 100 000 hours makes them practically maintenence-free. Furthermore, because the use of LED's is not accompanied by heat, noise, vibration or high voltage, their application range in industrial image processing has expanded dramatically in recent years. Diodes are often arranged in arrays or as ring lights. In addition, like halogen lamps, they are used as feeding light sources for fiber optical systems.

The emission of monchromatic light which is an advantage of LED's can, in some situations, be disadvantageous.

Lasers have a high radiation power focused on a very small area; laser light is highly chromatic and coherent. Nowadays, though, because of safety considerations (among other reasons) large laser units which scan scenes have been replaced by *laser diode modules*. A laser diode module is the end result of a laser diode, electronics and optics built into a common housing. A laser diode module is about the size of a thumbnail and, like an LED, can be integrated into systems with limited space to be used as laser source. With laser diode modules it is possible to project lines, points, circles, matrices of points, etc. Therefore the mechanical adjustment of the object before recording the image can also be supported optically. Like halogen lamps and LEDs, lasers can be used as feeding light sources for fiber optical systems.

Infrared light sources are always used in scenes where it is impossible to eliminate unwanted influence of surrounding daylight or of scattered radiation from other light sources. If, in addition, an infrared camera is used with a daylight blocking filter, the influence of the ambiguous ambient light can be completely eliminated.



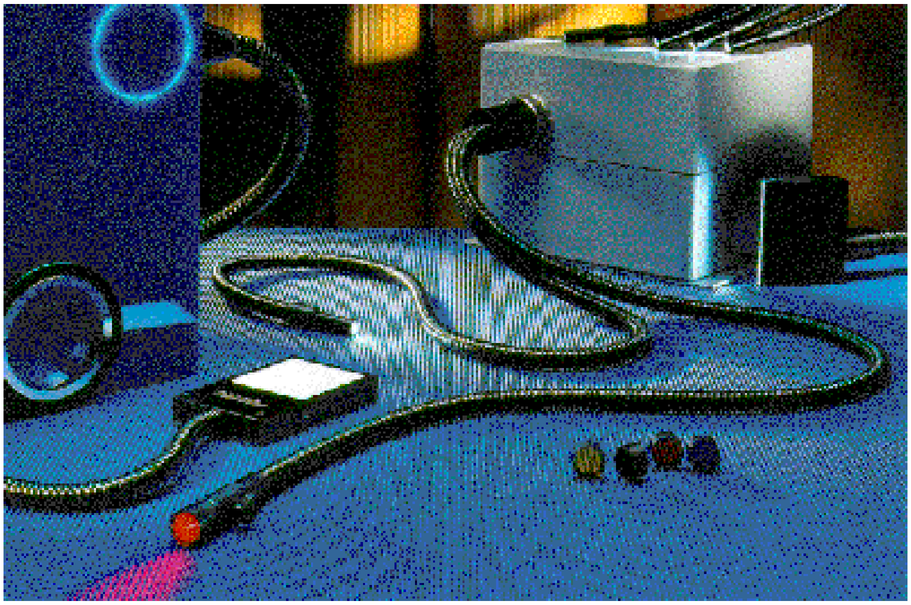
1.2: Construction of a ring light

If constant light intensity over a very long time period is required, the aging process in all light sources has to be taken into consideration. The aging process causes a decrease of intensity, and in most cases, the frequency spectum will shift towards longer wavelengths.

If fibre-optic light sources are used to illuminate small objects, it is possible to direct the angular distribution of the light flow explicitly and to fit the spatial distribution of the illumination strength according to the object. In addition, difficult-to-access areas can be illuminated. Fig. 1.2 and fig. 1.3 show some realizations. Light sources for the coupling of fibre-optic units include, among others, halogen lamps, discharge lamps, LED's and laser diodes. Because of scattering and reflection phenomena on the inner boundaries of the optical fibres, the intensity losses amount to about 40%.

Fast-moving objects have to be illuminated stroboscopically. The synchronization will be handled by the frame grabber hardware. There, the trigger signal for the camera as well as for the stroboscope has to be created.

Depending on the positions of the camera and the light source, one distinguishes among four fundamental ways of lighting a scene: incident light illumination, transmit-



1.3: Various fiberoptic illuminations for image processing like point lights, ring lights, area lights

ted light illumination, light-field, and dark-field illumination.

Incident light illumination: Camera and light source are on the same side of the object. The image shows the distribution of the light intensity reflected by the object.

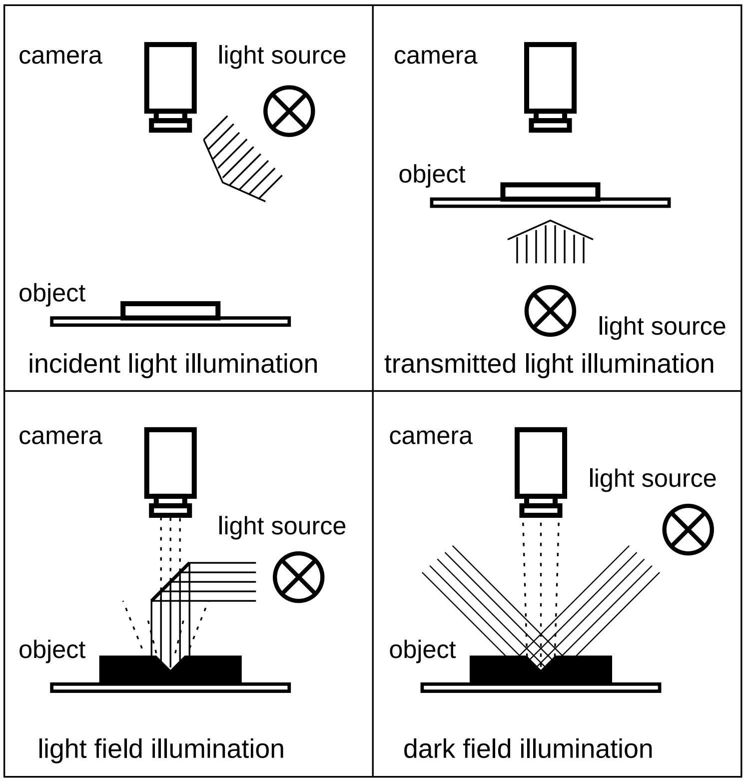
Transmitted light illumination: Camera and light source are on opposite sides of the object. The screen shows the dark form of the object in front of a light background. Transmitted light illumination is applied when an object can be described by its own form.

Light-field illumination: As with incident light, the camera and the light source are positioned on the same side of the object. The part of the light which is directly reflected into the camera will be used for the imaging process. Light-field illumination will show dark objects against a light background.

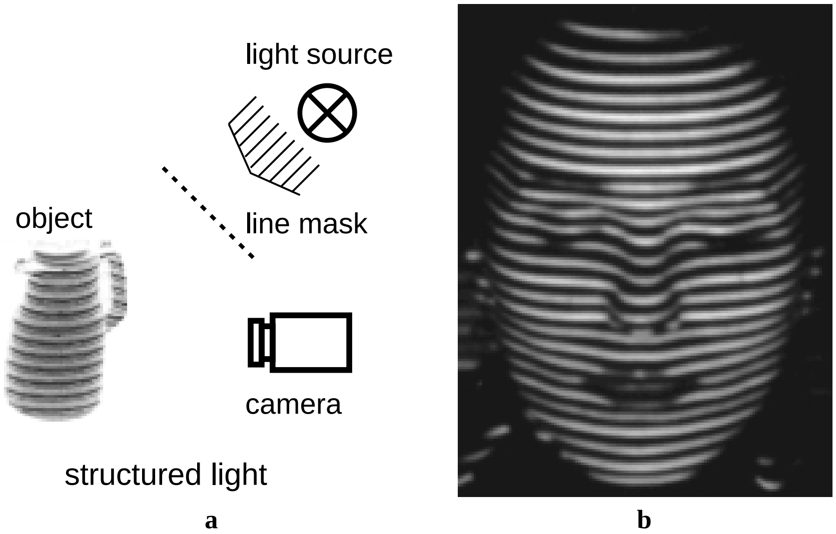
Dark-field illumination: As above, camera and light source are on the same side of the object, but only the scattered light is captured by the camera. Dark-field illumination produces a dark background with light objects.

We intuitively use light- and dark-field illumination to see a scratch on a record or a CD. If it is held against the light, the scratch can appear dark on a light background (light-field illumination) or light on a dark background (dark-field illumination).

If the four basic types of illumination are used with additional mechanisms, numerous other possibilities to light a scene are available.



1.4: Basic illumination setups



1.5: Structued illumination to measure three-dimensional objects[7]

a) illumination setup
b) projected lines

Diffuse Lighting: If the surface of an object to be illuminated reflects strongly, direct lighting cannot be applied. Diffuse light can be used instead, as might be generated by an overcast sky. The direct light is focused on a diffusing surface which can be something as simple as a white sheet. The result is that only the scattered light hits the object. Diffuse lighting “softens light conditions of a scene and prevents strong reflexes.

Structured Illumination: This is applied when a three-dimensional object has to be surveyed in two dimensions. Lines or a grid are projected onto the three-dimensional form. The curvatures of the projected lines on the three-dimensional surface depend on the position of the camera, the light source and the grid, and, of course, the three-dimensional form of the object, which can be calculated from the bending of the lines.

Using the shadow of an object: If an object has about the same lightness as its background, it is often impossible to see it in the picture. If the object is three-dimensional, the light source should be placed in a position allowing the shadow of the object to appear in the background. Instead of the object itself, the shadow will be measured. From the relative positions of camera and light source, the real dimensions of the image can be calculated.

1.2 Imaging Methods and Sensor Systems

The term “image processing suggests that the pictures which will be processed are taken by camera. This is often the case, but generally, every sensor which produces spatially-distributed intensity values of electromagnetic radiation which can be digitized and stored in RAM is suited to image capturing.

Various image capturing systems are used, depending on the application field. They differ in the

- acquisition principle
- acquisition speed
- spatial resolution
- sensor system
- spectral range
- dynamic range

Apart from the area of consumer electronics, most apparatuses are very costly. The greater the need for accuracy, the more hard- and software is used in the image capturing system. The following list shows the most- used units for capturing images electronically:

- area scan cameras

- line scanners
- laser scanners
- computer und nuclear magnetic resonance (NMR) tomographs
- thermographic sensor systems (e.g. infrared cameras)
- ultrasonic devices

CCD sensors play a central role in most image processing systems. They are part of a complex system which makes it possible to take images in problematic environments with the necessary quality and accuracy.

Sensors can be categorized into the following classes according to their sensitivity ranges:

Electromagnetic sensors for

- gamma radiation
- X-ray radiation
- the visual spectrum
- the infrared spectrum
- the radio wave range

Each electromagnetic sensor is only sensitive to a certain range of electromagnetic radiation. Other sensors like

- ultrasonic sensors
- magnetic sensors

may also be used for imaging, but they do not work according to the CCD principle.

However, in the context of this course, only the most important acquisition methods will be considered.

1.2.1 CCD Cameras

In a film camera the photo-sensitive film is moved in front of the lens, exposed to light, and then mechanically transported to be stored in a film roll.

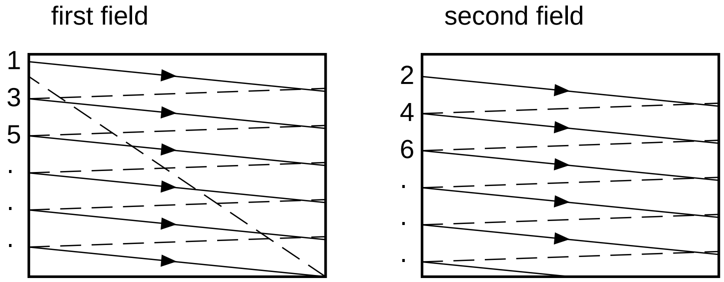
A CCD camera has no mechanical parts. The incoming light falls on a CCD (*Charge Coupled Device*) sensor, which consists of numerous light-sensitive semi-conductor elements, the so-called pixels. They are arranged in a line (*line camera*) or a matrix (*area scan camera*).

The image sensor is the heart of a digital camera. High resolution and color accuracy as well as the signal-to-noise ratio depend on the quality of the CCD sensor. The physics of a CCD sensor is the *inner photo effect*. This means that the incoming photons produce electrons in the semi-conductor material, which are separated in the photo diode and stored as in a capacitor. This capacitor is connected to the surrounding electrical circuit via a MOS transistor, which acts like a light switch. If it is open, the charges will be collected in the capacitor (*'integrated*) and will be transported when the switch is closed. The number of electrons which are collected is proportional to the light which reaches the light-sensitive part of the sensor. The exact physical processes, however, are not of much relevance to our topic; you will be referred to the numerous literature sources in opto-electronics, for example [5] or [2].

The Video Norm

Real time systems are usually based on video norms, which means that the image acquisition as well as the conversion of the digital data into a video signal has to conform to international standards. In Europe, this norm is defined by the *Comité Consultatif International des Radiocommunications* (CCIR); in the USA, the norm is called *RS-170 Standard*indexRS170and was defined by the *Electronics Industries Association* (EIA). The PAL(*Phase Alternation Line*)and SECAM (*Sequentiel Couleur á Memoire* color standards are based on CCIR while the color system based on RS-170 is NTSC (*National Television System Committee*). The fundamentals of all video standards reach back to the times of tube cameras and tube monitors and seem a little archaic in the age of CCD chips and LCD screens.

Both norms require the so-called *interlace process*, for the image on the screen to be non-flickering (fig. 1.6). This means that a complete image *(frame)* is separated into two half images *(fields)*. One field consists of the odd lines; the other consists of the even lines of the image. The electronic ray starts in the upper lefthand corner. After it reaches the end of the first line (this takes 52 μs (CCIR)), it goes back to the beginning of the third line which takes 12 μs (CCIR). During this time the horizontal sync signal (*H-Sync*) is added to the video signal, which starts the new line. The front and back porch of the line blanking pulse is used as a reference of the color black. In this way the electronic ray scans the first field with the odd-numbered lines. Then the vertical sync signal (*V-Sync*) is added, which indicates the beginning of the next field. The V-Sync - Signal is a more complex signal, which requires 50 video lines. Subsequently, the second field with the even numbered lines is scanned. A complete scan with two



1.6: Interlace process: two fields make a frame fields consists of 625 lines and takes 40 ms. Because the initialization of the next field takes 50 of the 625 lines, only 575 per frame or 287.5 lines per field are visible. In both video norms the ratio of width to height is 4:3. This means that there are 767 pixels per line. This number of pixels is scanned in 52 μs and results in a pixel frequency of 14.75 MHz.

Table 1.1: The video norms CCIR and EIA

	CCIR	RS-170
frame setup	interlace	interlace
color system	PAL/SECAM	NTSC
fields per sec	50	60
time per field	20 ms	16.6 ms
time per frame	40 ms	33.3 ms
total number of lines	625	525
time per line	40 ms/625 = 64 μs	33.3 ms/525 = 63.5 μs
line frequency	1/64 μs = 15.625 kHz	1/63.5 μs = 15.750 kHz
information per line	52 μs	52.7 μs
line sync	12 μs	10.8 μs
field sync	3.25 ms $\equiv$ 50 Zeilen	2.54 ms $\equiv$ 40 Zeilen
no. of visible lines	575	485
image format (horizontal:vertical)	4:3	4:3
pixel per line	575*4/3 = 767	485*4/3=647
time per pixel	52 μs/767 = 67.8 ns	52.7 μs/674 = 78.2 ns
pixel frequency	1/67.8 ns = 14.75 MHz	1/78.2 ns = 12.8 MHz
no. of line pairs	767/2 = 383.5	647/2 = 323.5
horizontal resolution (max. Video frequency)	14.75 MHz/2 = 7.375 MHz	12.8 MHz/2 = 6.15 MHz
channel width	5 MHz	4.2 MHz

However, for our visual perception a pixel has little relevance. Therefore video resolution is traditionally defined differently. The video system under the CCIR Norm reaches its physical limitation when it has to show a test pattern of 383.5 black and white line pairs, since two neighboring pixels then have to show the lowest and highest intensity value. 383.5 periodic intervals in 52 μs result in a frequency of 7.375 MHz, which is the maximum possible bandwidth of any video component. On the other hand, the CCIR - Norm allows a much lower video bandwidth (channel width) of 5 MHz. Thererfore, the number of *vertical* lines which a camera can capture is a quality measure of the resolution. This parameter is called *TV-Lines*. It counts the number of *vertical*, not the horizontal lines. Table 1.1 shows the specifications and their values according to the video norms CCIR and RS-170

Norming video electronic units has the advantage that components such as CCD chips from different manufacturers can be integrated into appliances. Norming is one of the reasons for the vast increase in the use of CCD cameras in the entertainment industry, including the private sector. Accordingly, the components have become affordable for a wide range of users.

On the other hand, norming can also be restrictive. For example, the interlace process required by the video norm ensures a flicker- free image but there are applications where it has some disadvantages. If a fast- moving object is filmed by a norm video camera, the object will have moved during the first 20 ms which were required to record the first field. Therefore the beginning of every second line is shifted. This is known as *comb* *effect*.

Another disadvantage of the video norm is the short integration time, which is maximum 20 ms. If light conditions are unfavorable, it is impossible to produce pictures of acceptable quality, even when all the amplification possibilities are applied. In a case like this you use a camera with a long-term integration capability, which does not conform with the video standard.

For applications where the video norm's disadvantages are too great there are norm-free cameras. *Progressive xcan* cameras are an example which do not apply the interlace process but instead scan the lines subsequently. These sensors are also able to use the full resolution of modern graphic cards. Typical image formats are, for example, the VGA resolution with 800×600 pixel or the SuperVGA format with an even higher resolution of 1280×1024 ixel.

Cameras which do not conform to the video standard are usually more expensive because they cannot be mass-produced.

High Definition Television (HDTV)

The original idea for the HDTV format (*High Definition Television*) came from wide screen movies. In the early 1980's Sony and NHK (*Nippon Hoso Kyota*) developed an HDTV - film recording system (called *NHK Hi- vision*), which could be used to take a scene and play and edit it immediately afterwards. This eliminated the many delays which occur with normal film production. In addition, the new medium made a number of special effects possible, which were impossible to do in traditional film production.

In addition, it turnded out that the movie audience were more impressed with wide screen movies, because they create the impression that the viewer is part of the scene. Soon efforts took place to develop a similar format for the television screen. The motivation was less the enhancement of resolution but rather

- the creation of a natural viewing experience by using the total human visual field
- the absence of visible distortions like the comb - effect with the interlace method
- high image quality.

Now, the developers of HDTV have had the same problems as the engineers involved in the introduction of color television in 1954. Worldwide there are 600 million TV sets, and the question arose, if HDTV should be *compatible* to the old standard, if it should *supplement* the old standard or if the two standards should be transmitted *simultaneously*. The main problems were

- the enormously high data rate of more than 40 Mbit/s, which requires a high bandwidth or highly sophisticated compression techniques
- the larger screen format, which meant that the users had to replace their old TV screens with new and more expensive ones, if they wanted to benefit from the new format
- the fact that the new standard was incompatible with the PAL - System. This was probably the biggest obstacle to the introduction of HDTV in all the the countries which, like Germany, use PAL.

- the fact that the expensive equipment used by TV studios would have to be replaced by even more expensive equipment and, on the consumer side, peripheral units like video recorders would also have to be replaced.
- the increased image quality which would have to be assured at the production site
- the marketing problem: unlike in Japan, users in Europe and in the United States have to be “convinced that it makes sense to throw their old TV equipment out and replace it with HDTV.

As a result, the introduction of analog HDTV has been quite difficult. It has had completely different receptions in Japan, the US, and Europe.

- Japan has a quick start:
  - 1964 Fundamental research and development of HDTV starts
  - 1979 First TV broadcast in HDTV format
  - 1981 HDTV is officially introduced, which causes an “HDTV-shock in the US and Europe.
  - 1989 Regular HDTV broadcasts in MUSE (the Japanese HDTV analog format) begin
  - 1997 Announcement to change to digital HDTV

  Therefore, research, development and production of cameras, recorders, TV sets, broadcasting systems etc. are much more advanced today than in the US or Europe. In addition, the Japanese have gained extensive knowledge and experience. Japan is the only country in the world which broadcasts more than 9 hours per day in the HDTV format.

- The US counters:
  - 1977 Foundation of a study group concerning HDTV (SMPTE)
  - 1983 Foundation of the *Advanced Television Systems Committee (ATSC)*
  - 1986 The USA decides to support the Japanese system
  - 1989 The USA decides to drop the support for the Japanese system
  - 1990 Introduction of the digital HDTV-System *DigiCipher*
  - 1995 Agreement of the *Grand Alliance* on a common HDTV-Standard
  - 1997 Official start of HDTV broadcasting through terrestrial frequencies with OFDM and 8-VSB

  The introduction of HDTV in the USA was made difficult by the facts that too many suggestions for systems existed and that the agreement on “the best system took quite a while.

- Europe is asleep:
  - 1986 Start of development of HD-MAC (the European HDTV analog format)
  - 1988 introduction of HD-MAC prototypes

- 1991 HD-MAC is dropped and a *European Launching Group (ELG)* is founded to support the development of a European digital standard
- 1993 The ELG is transformed to the *Digital Video Broadcasting Group (DVB)*. Norms for digital TV broadcasting, based on the MPEG2 compression method are developed.
- 1994 Norms for satellite and cable transmittance are introduced
- 1996 The norm for terrestrial transmission is introduced.

After dropping HD-MAC, analog HDTV was no longer supported in Europe. Rather, a common broadcasting standard for digital TV was sought, which would include digital HDTV based on MPEG2. However, the regular broadcast of HDTV programs is not to be expected in the near future. Instead, several programs with a quality similar to that of the PAL system are supported.

The fields for the HDTV-format in Europe are mainly the areas of medical imaging, the military, design, graphics, the print media, advertising, art and the movie industry. Although TV is expected to support the HDTV format in the far future, experts estimate, that not more than 20% of all programs will ever be broadcast in HDTV.

For industrial image processing this development has come too late. For areas which are not suitable for a videonorm camera, numerous special developments have been made, which are moderately priced for industrial standards.

Table 1.2: Comparison of HDTV - Norms of Japan, the USA und Europe

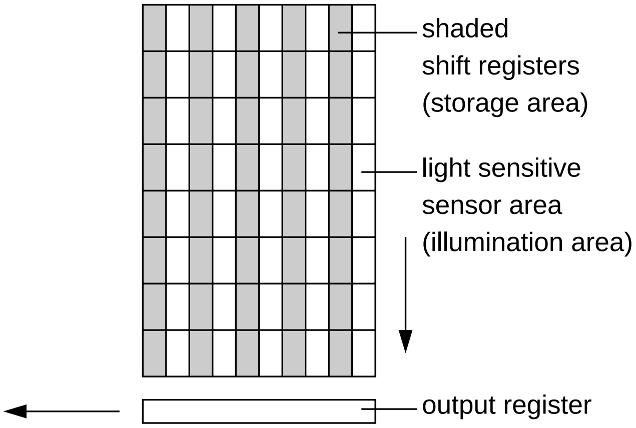
	HDTV Japan	HDTV USA	HDTV Europe
frame setup	interlace	progressive scan	progressive scan
number of lines	1125	1050	1250
visible number of lines	1080	960	1000
image format (horizontal:vertical)	16:9	16:9	16:9
optimum viewing distance	3.3·picture height	2.5·picture height	2.4·picture height
vertical viewing angle at optimum viewing distance	17°	23°	23°
orizontal viewing anglel at optimum viewing distance	30°	41°	41°

CCD Sensor Architectures

CCD area scan cameras are available in several CCD sensor architectures, of which three are currently on the market.

The term *architecture* refers to the way the information of the individual pixels is bundled and integrated into a serial data stream. For all architectures there are camera versions, which conform to the video norm and others, which define their parameters freely. Descriptions of the above-mentioned architectures follow. However, not all available cameras are included. In this sector there are many in- house developments and developments for specific applications.

The Interline Transfer Sensor: An interline transfer sensor is subdivided into light-sensitive and storage areas (fig. 1.7). These are arranged in stripes. The charges are integrated in the light-sensitive cells and subsequently transferred in a very short time (about 2.5 μs) to the shaded vertical shift registers. From there they are transferred one line at a time to a horizontal readout register and then sequentially to the input area of the video input unit (fig. 1.8).

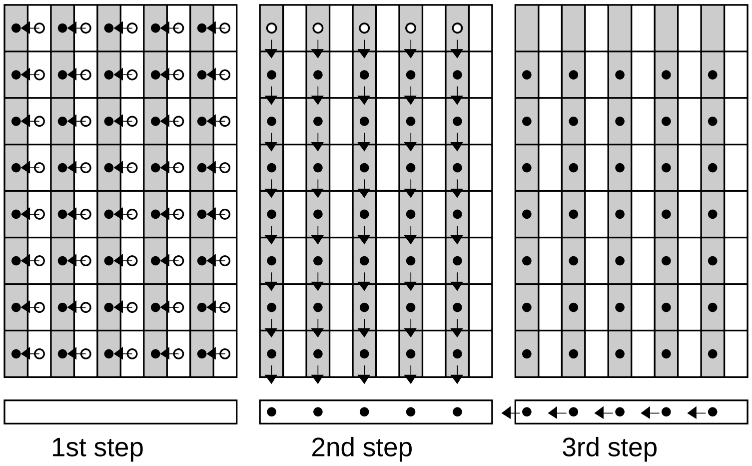


1.7: The Interline concept: illumination. and storage area are arranged in a stripe pattern

With the interline transfer sensor the active light-sensitive area takes only a small part of the total sensor cell. The connectors between the cells as well as the shaded areas are not light-sensitive. This results in the fact that interline transfer CCD cameras in the traditional architecture are much less light-sensitive than, for example, frame transfer cameras, which are described below. There are several developments which aim to offset this disadvantage. The *lens -on - chip* - technology is worth mentioning. There, every sensor cell gets a micro lens, which bundles the light normally falling on the shaded storage area into the light-sensitive sensor area. This results in a sensitivity increase of about a factor of 2.

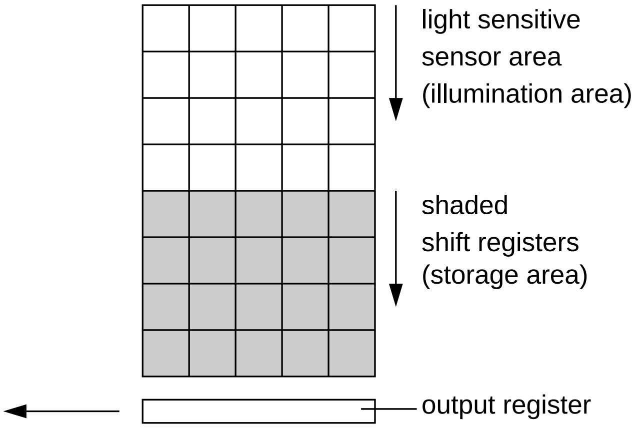
The Frame Transfer Sensor: On a frame transfer sensor the light-sensitive areas and the storage area are located in two different blocks. The total area (light-sensitive cells and shaded shift register) is about twice as big as on the interline transfer sensor fig. 1.9). The total charge is shifted through the transport register into the shaded shift register. From there it gets transferred into the horizontal output registers and added to the serial data stream (fig. 1.10). Most frame transfer CCD sensors also conform to the video norm.

But as with other architectures, there are forms which do not adhere to the video norm.

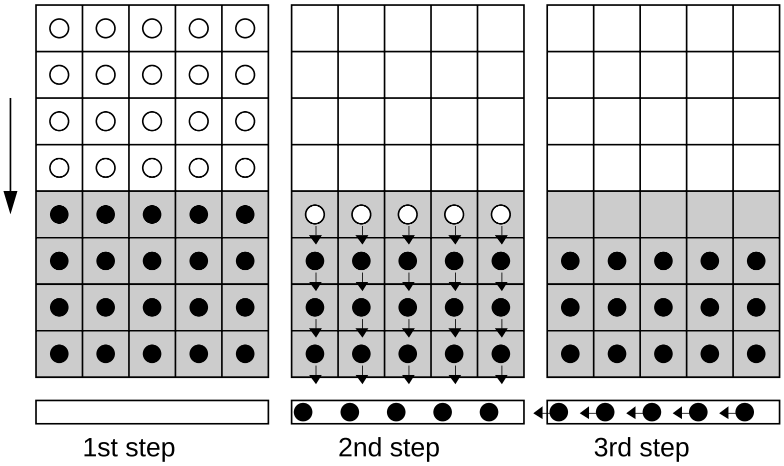


1.8: Transport of charges with the Interline Transfer CCD sensor

1st step: integrated charges are transferred to the vertical shaded readout registers.
2nd step: integrated charges are transferred to the horizontal readout register.
3rd step: serial output of charges



1.9: The Frame Transfer concept: illumination and storage area are two blocks



1.10: Transport of charges at the Frame Transfer CCD sensor

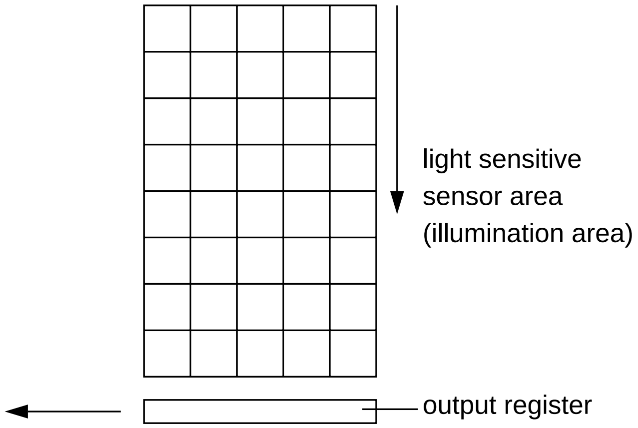
1st step: integrated charges are transferred to readout registers.
2nd step: integrated charges are transferred to the horizontal readout register.
3rd step: serial output of charges

The Full Frame Transfer Sensor: (The full frame transfer sensor, unlike the frame transfer and the interline transfer sensor, does not incorporate a storage section. The total sensor area is light sensitive (fig. 1.11). After the integration time the the shutter is closed and the charges are read out line after line (fig. 1.12). Full frame sensors always need a shutter camera. This sensor type has no influence on the integration time. An external shutter takes care of that. The full frame transfer image sensor makes fast data rates possible. It is mostly used in time-critical applications. High resolution cameras (500×500 . . . 4000×4000 pixels) also use a full frame transfer image sensor.

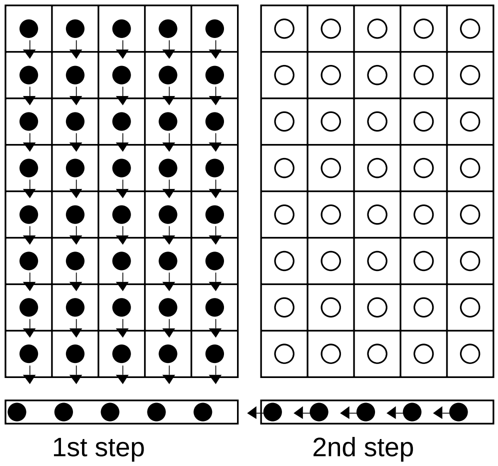
In this section, only the principal detector architectures have been described. There are countless variations and combinations. Research is moving in the direction of the development of so-called “intelligent cameras which will be capable of taking over computer functions. Some projects of new camera developments will be discussed in chapter 1.2.2. Research labs have been working on cameras with the ability to adapt to light changes, cameras with stereoscopic vision, cameras with integrated capabilities of smoothing and edge detection, etc. While most cameras which are currently available are still based on the interline transfer technology[21][20], conform to the CCIR norm and transfer images with the interlace mode, in the near future they will probably exceed the ability of the human eye[12].

CCD Chip Formats

CCD chips are available in different formats (fig. 1.13). The designation of chip sizes goes back to tube cameras. Typical outside diameters of these tubes are 1 inch,

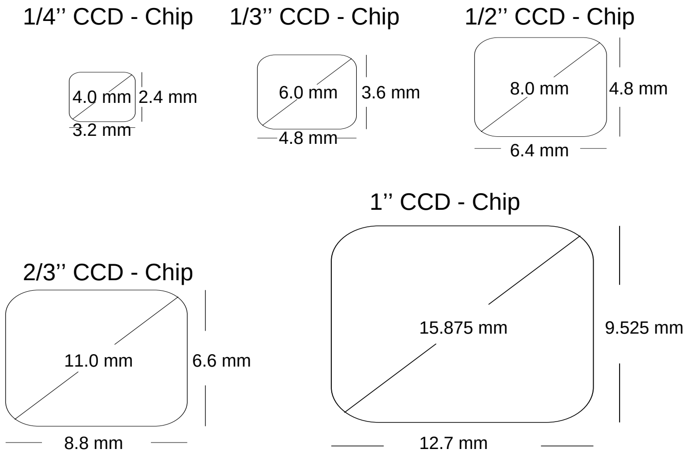


1.11: The Full Frame Transfer concept: the total sensor area is light sensitive



1.12: Transport of charges at the Full Frame Transfer CCD sensor

1st step: after the integration time the camera shutter is closed and the charges are transferred to the horizontal readout register
2nd step: serial output of charges.



1.13: Chip sizes.

2/3 inch and 1/2 inch. A tube with a 1 inch outside diameter has a rectangular active window measuring 16 mm diagonally. This format was retained for CCD sensors. 1 inch chips are very rarely applied nowadays; 1/3 inch and 1/2 inch chips, on the other hand, are finding more and more applications, especially in the field of security cameras, miniature cameras and home video cameras. In metrology however, the 2/3 inch chip is predominant and will be in the foreseeable future.

Pixel sizes fall between 4 μm × 4 μm and 16 μm × 16 μm; the number of pixels range between 500 × 500 in security cameras up to 5000 × 5000 in sophisticated measuring applications[3].

Camera Configurations

There is a wide range of camera configurations, depending on their application field. Camera types can differ in the way the pixels are arranged as well as in their spectral sensitivity.

The part of the electromagnetic spectrum to which a camera is sensitive depends on the semiconductor material the CCD chip is made of. As mentioned in previous sections, the incoming photons produce free charge carriers by lifting the electrons of the semiconducter material from the valence band to the conduction band. The number of electrons produced is proportional to the number of incoming photons.

The spectrum of CCD sensors ranges from ultraviolet light up to the infrared area. The spectral sensitivity depends on the energy gap Δ E between the valence band and the conduction band. For Δ E = 1 eV, for example, an upper limiting wavelength of λ_g = 1.24 μm can be calculated from the equations

$$\begin{aligned} h \cdot \nu &> \Delta E \qquad\qquad \text{and} \\ c &= \lambda \cdot \nu \end{aligned}$$

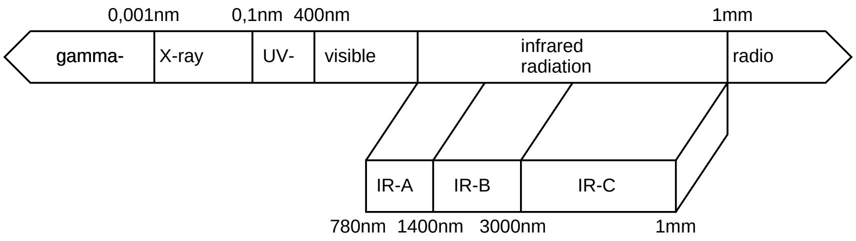
$$\rightarrow \qquad \lambda \; < \; \frac{h \cdot c}{\Delta E} = \lambda_{max} \tag{1.1}$$

with:
ΔE: energy difference between valence band and conduction band in eV
$h = 6.6262 \cdot 10^{-34}$ Js: Planck's constant
λ: wavelength of light
λ_{max}: cut-off wavelength
ν: light frequency
c = $299.8 \cdot 10^{6}$ m/s: speed of light in vacuum
1eV = $1.60219 \cdot 10^{-19}$J: conversion factor

Table 1.3 shows various energy gaps and the resulting upper limiting wavelengths for various semiconductor materials. From this table and from fig. 1.14 it can be concluded, for example, that silicium is very well suited for the near infrared (IR-A) and the visual part of the electromagnetic spectrum, while for the far infrared spectrum (IR-C), semiconducter materials with a lower gap between valence band and conduction band should be used.

Table 1.3: Energy gap between valence and conduction band with the cut-off wavelength for various semiconductor materials. Values at T=300 K. (Nr. 1 [8], Nr. 2 [13], Nr. 3 [14] Nr. 4 [9] Nr. 5 [1] Nr. 6 [16] Nr. 8 [4] Nr. 9 [17])

Nr.	Semi Conductor	Chem. Abbr.	ΔE in eV	λ_{max} in nm
1	indium - antimonide	InSb	0.18	7754
2	lead telluride	PbTe	0.311	5904
3	lead sulphate	PbS	0.42	3351
4	germanium	Ge	0.664	1879
5	silicium	Si	1.1242	1107
6	gallium arsenide	GaAs	1.424	867
7	cadmium - selenide	CdSe	1.7	729
8	gallium phosphat	GaP	2.272	553
9	cadmium sulfide	CdS	2.485	512



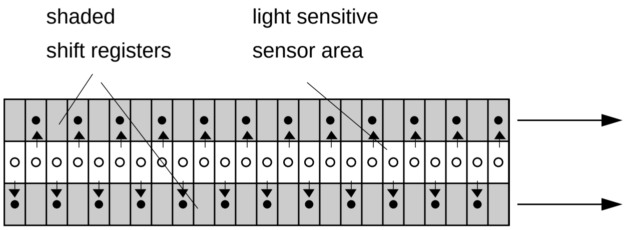
1.14: The electromagnetic spectrum

CCD cameras for the visual spectrum are sensitive in a range of 400 nm up to 1000 nm with a maximum of approximately 530 nm (green).

The following description shows cameras with various pixel arrangements.

Line cameras consist of only one line of CCD sensors. They are applied to problems where a higher resolution is required or only one object dimension has to be sampled. These days, line cameras with 8000 or more pixels and a pixel frequency with more than 30 MHz are series products. To minimize losses during the shifting process of the electrical charges, line cameras read out towards both sides of the line (fig. 1.16). This keeps the readout times low but also causes low integration times, which in turn require high light intensities of the illumination units.

1.15: Various line cameras

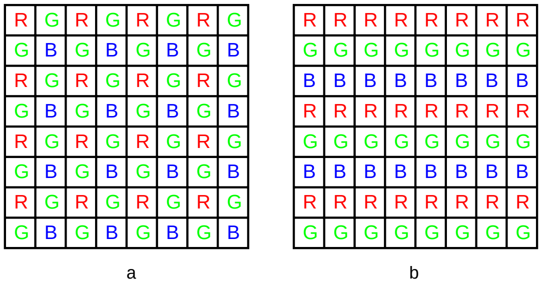


1.16: Output of charges with the line camera

Monochrome area scan cameras consist of a matrix of CCD sensors. These have been described in the previous sections.

Color cameras produce a color image, which consists of three parts: red, green and blue. By additive color mixture and intensity variations in the different parts, almost any color can be reproduced.

- In the less sophisticated kinds of cameras (single chip color cameras) the incoming light gets separated into its red, green and blue parts by means of a stripe or mosaic filter which is located directly on the CCD sensor (fig. 1.17). The filter stripes or the equivalent elements of the mosaic filter are transparent for one of the three colors, respectively. At readout time, the pixels of the red, green, and blue sectors are transferred successively. Electronic switches divide the signal into the primary colors. The mosaic filter causes the resolution to be reduced by a factor of two in two directions; the stripe filter reduces the resolution by a factor of three in one direction, compared to a monochrome camera. Although the colors can be represented on a TV screen, the three primary colors cannot be separated for individual image processing purposes. Single chip cameras are therefore not very well suited for image processing tasks but are mostly used in entertainment electronics areas.



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

a

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

b

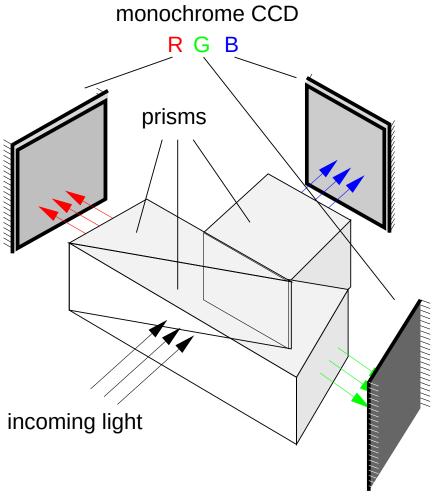
1.17: A one chip camera produces colors through
a) mosaic or
b) stripe filters

- Three chip color cameras use a separate CCD sensor for each of the three primary colors. Prisms in the optical path provide a separation of the incoming light into its three components, which will be directed to the appropriate sensor. The data of the three CCD sensors are directed towards different areas of the image RAM and can be processesed separately (fig. 1.18)

Infrared cameras are only sensitive to certain frequency bands of the infrared radiation. As everybody should know, each physical body with a temperature above absolute zero emits radiaton. The relevant physical laws are Planck's radiaton law

$$u(\lambda, T) = \frac{8\pi}{\lambda^3} \frac{h}{e^{\frac{hc}{\lambda kT}} - 1} \qquad (1.2)$$

with:
$u(\lambda, T)$: Spectral radiation energy density



1.18: The incoming light is divided by prisms into its basic components red, green, and blue.

$h = 6.6262 \cdot 10^{-34}$ Js: Planck's constant
λ: wavelength of light
T: Temperature in Kelvin
$k = 1.38066 \cdot 10^{-23}$ J/K: Boltzmann's constant
c = $299.8 \cdot 10^{6}$ m/s: speed of light in vacuum
1eV = $1.60219 \cdot 10^{-19}$J: conversion factor

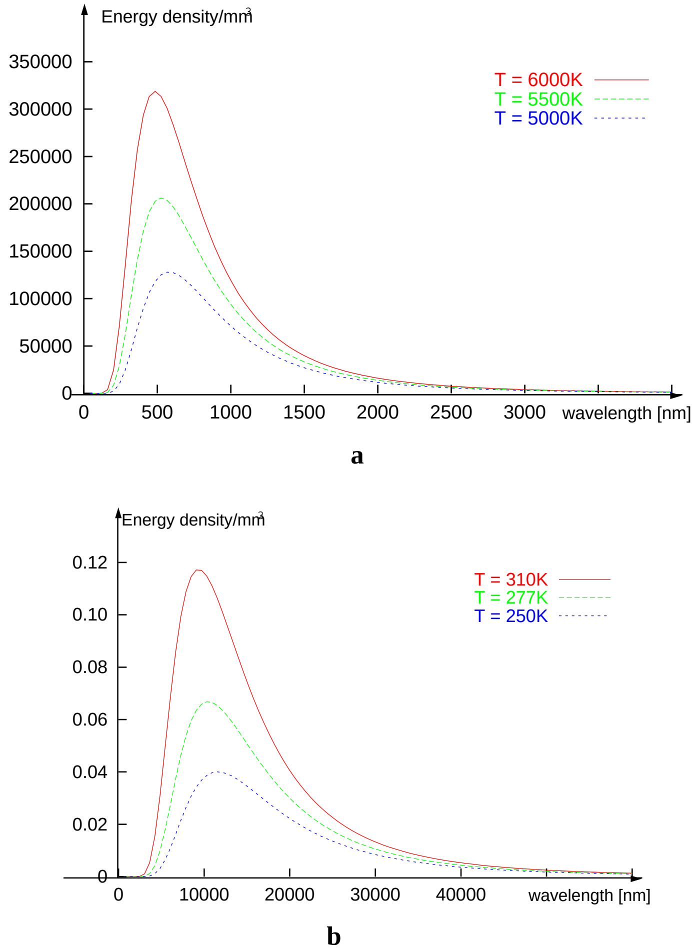
and Wien's displacement law, which states, where the maximum of the radiation energy density in fig. 1.19 is located:

$$\lambda_{max} = \frac{b}{T} \tag{1.3}$$

with:
T: Temperature in Kelvin
$b = 2.8978 \cdot 10^{-3}$ m·K: Wien's constant

For example, a physical body at room temperature (300 K) emits infrared radiaton with a wavelength of 10 μm (IR-C) (fig. 1.14). Infrared cameras are able to capture this radiation and, through the same principles as monochrome cameras, transfer it into electronic signals. This is called thermography. According to the norming commission *Commission Internationale de l'Eclairage* (CIE) the infrared spectrum is subdivided into three bands (fig. 1.14). While the atmosphere is mostly opaque for infrared radiation, there are five narrow bands in the infrared spectrum for which the atmosphere is transparent (tab. 1.4). They are used for astrophysical tasks.

The image sensor of an infrared camera consists of semiconductor materials which are sensitive to the infrared spectrum, i.e. for wavelengths of 0.78 μm



1.19: The energy distribution of a black body

a) for sun-like temperatures

b) a human body (310 K), the milk in the refridgerator (277 K) and a frozen chicken (250 K)

Table 1.4: IR transparent bands in the atmosphere

Name	wave length λ
I - channel	$\sim 1.25\ \mu\text{m}$
H - channel	$\sim 1.65\ \mu\text{m}$
K - channel	$\sim 2.2\ \mu\text{m}$
L - channel	$\sim 3.6\ \mu\text{m}$
M - channel	$\sim 4.7\ \mu\text{m}$

or higher. To keep the noise level caused by the ambient temperature low, the CCD chip of this type of camera has to be permanently cooled. Modern cooling methods are thermoelectric cooling (Peltier cooling) and Stirling cooling. This is the reason that infrared cameras are larger than equivalent cameras for the visible electromagnetic spectrum.

1.2.2 Modern Camera Developments

CCD sensors still have big disadvantages in spite of the progress made in this technology. One of them is the effect called *blooming*. It results from a local overexposure of pixels to light, for example when a light source is photographed in front of a dark background. The pixels get oversaturated and the charges leak into neighboring pixels. The result is a light spot in the image, which enlarges uncontrollably (therefore the expression *blooming*) and erases the actual image information. Modern detectors incorporate an *anti-blooming* circuit, which prevents the leakage of charges into neighboring pixels. However, this camera type is about 30% less sensitive.

A further disadvantage, which all the previously mentioned architectures share, is the bottleneck of the serial readout registers, which slows down the transfer rate immensely.

Currently industry and research facilities are investing lots of money and energy into new camera concepts - with different results. Let's have a closer look at three examples.

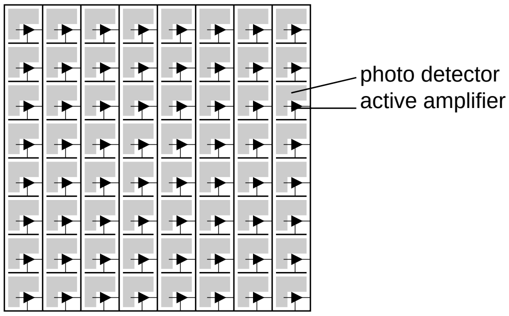
CMOS Technology

A big change in the digital camera market could come from the introduction of a new type of sensor in CMOS cameras (*Complementary Metal-Oxide- Semiconductor*).

For CMOS sensors the production process is the same as for all micro processors, storage chips and ASICs (engl. *Application Specific Integrated Circuit*). With CCD - cameras incoming photons create negative charge carriers, which have to be integrated over a certain time which is determined by the shutter speed. By contrast, CMOS - Sensors are, in principle, photo sensitive diodes, which are in series with a resistor. While in CCD - cameras electrons have to be transported via shift registers, the principle of the CMOS Camera allows a continuous transformation of the incoming photons into a resulting voltage. A CMOS - sensor is nothing but an array of exposure meters (fig. 1.20.

In the past, CMOS sensors were not very popular because of their high noise level, which was caused by the layout of the chip. However, in 1993 physicists at the *NASA Jet Propulsion Laboratory* in California succeeded in developing a unit called *APS* (*Active Pixel Sensor*), which incorporates, for each pixel, an active transistor amplification circuit, providing, among other things, efficient noise reduction. In spite of that, the signal - to - noise ratio of a CMOS - camera is still significantly higher than that of a CCD+- camera. Here are some basic features of CMOS - Chips:

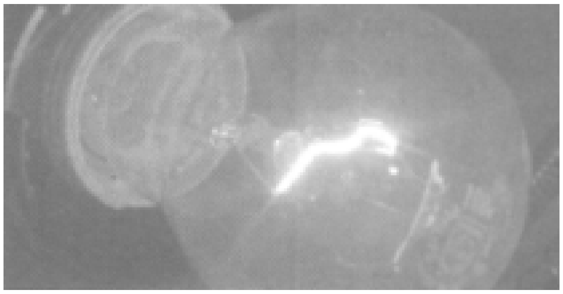
Direct access: CMOS - cameras permit direct access on any pixel, just like computer storage units. Like the image buffer, it can be addressed via line- and column coding (see. section 1.3.2).



1.20: CMOS - array with *APS*. Every pixel can be addressed individually through line and column selection

All image processing functins on one chip: VLSI - technology (*Very Large Scale Integration*) permits the integration of all necessary camara functions directly on the CMOS Chip. In addition, it is possible to add more intelligent signal processing circuits to provide, for example, image compression, image optimizing, color coding, segmentation etc. [22]. In principle, with CMOS cameras, all image processing algorithms, which will be addressed in the following chapters, can be implemented directly on the camera chip.

Wide dynamic range: Because of special features of the CMOS structure[11] the transformation process of photons into voltage is not linear but logarithmic, i.e. actually similar to the light response of the human eye. While a CCD camera has a dynamic range of about 2 - 3 decades, the range of the CMOS camera includes 6 decades and more. It permits the taking of an image of a 100 Watt light bulb and enables the recognition of the filament (fig. 1.21).



1.21: Image of a light bulb taken with a High Dynamic Range CMOS camera

Low power consumption: A CMOS-camera uses less electricity (by a factor of 100) than a CCD - camera. A CCD - camera will use about 2 - 5 Watt of power while a CMOS - camera needs only 20 - 50 mW A NiCd camcorder battery is used up in a few hours when connected to a CCD - camera, while it might last a week or more when connected to a CMOS - camera. Less power consumption makes an image processing system more flexible. In a few years, all image processing algorithms will take place on chips in intelligent cameras, which might be connected to notebook computers.

Low costs: The production process of CMOS - wafers is much simpler than CCD production. Therefore the price of a CMOS - camera today is not much higher than the price of a CCD - camera for industrial applications in combination with a frame grabber hardware[22].

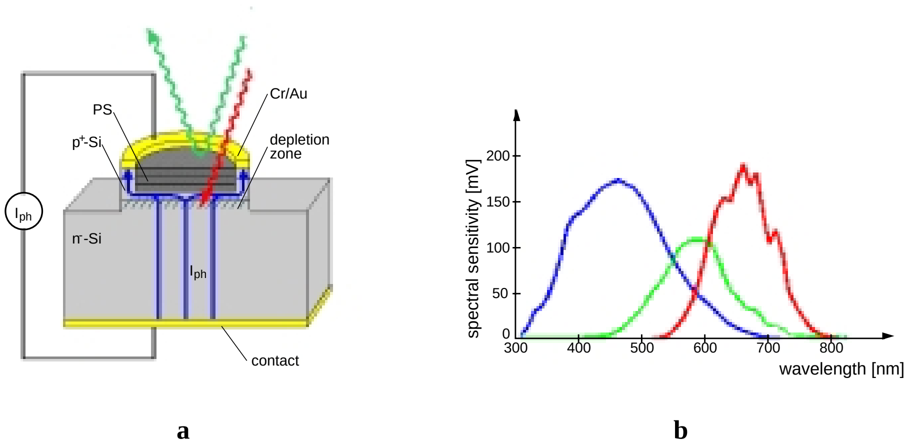
No blooming: Since CMOS cameras read out every pixel individually, blooming cannot occur.

High data transfer rates: The parallel transfer allows very fast image capturing and processing because routing through the horizontal and vertical shift registers is prevented. At this time the upper limit of the image transfer rate is about 1000 images per second, if an image size of 1024 × 1024 pixels is assumed[23].

Research is moving in the direction of development of so-called “intelligent cameras , which will be capable of taking over computer functions. Research labs have been working on cameras with the ability to adapt to light changes, cameras with stereoscopic vision, cameras with integrated capabilities of smoothing and edge detection etc. While most cameras which are currently available are still based on the interline transfer technology[20][22], conform to the CCIR norm and transfer images with the interlace mode, a new camera generation will probably exceed the ability of the human eye[15] in the near future.

Multichannel Sensors for Color Recognition

Current color cameras incorporate color filters or three separate chips for the basic colors red, green and blue. Research groups, among them a group at the Research Center in Juelich, Germany, are developing sensors, which store the coor information of a light ray in photo sensitive layers of a pixel, which are mounted on top of each other[18] For that task *porous silicon* is used[10]. It is manufactured from commercially available silicon wafers, which are a widely used product in the semiconductor industry. Pores with diameters of a few nanometers are electrochemically etched into the material, the size of which is much lower than the wave lengths of visible light. This means that a porous layer will have a refractive index which depends on the size of the pores. By controlling the density of the electical current during the production process, layers with different refraction indices can be created. When white light reaches the silicon material with multiple refraction layers, certain colors will be absorbed in certain layers, while the rest of the spectrum is able to transfer to lower layers. After the integration time, the color information of the incoming light will be stored vertically in multiple layers of the pixel. Fig. 1.22a) shows a cross section through a photo diode with integrated layers of porous silicon. Fig. 1.22b) shows the spectral responsiveness of a sensor with three colors as a function of the wavelength. So far the research groups have succeeded



1.22: A porous silicon photo sensor[18]

a) Cross section

b) Spectral response of a porous silicon photo sensor with three layers

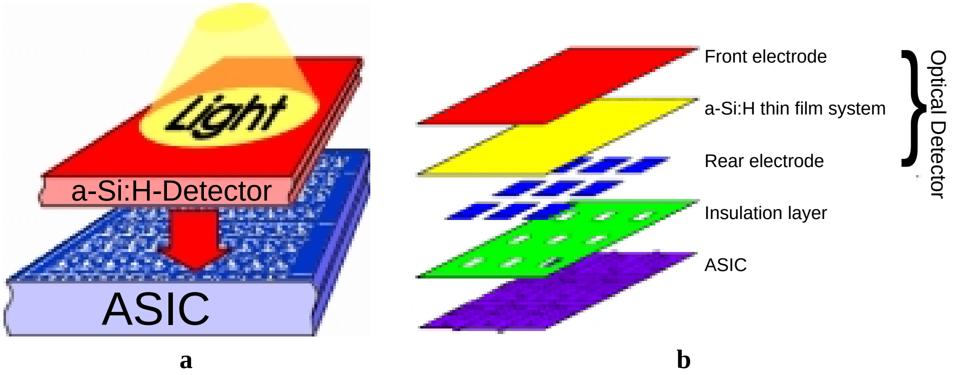
in developing a wafer with six different layers[18]. Theoretically, it should be possible to vary the refraction index continuously with the thickness of the silicon. The wavelengths which can be covered by this method are said to range from 300 nm to 3000 nm.

Intelligent *Thin Film on ASIC* (TFA) Imaging Sensors

With the CCD - Sensor as well as with the CMOS - Sensor not 100% of the chip surface is light-sensitive, since both sensor types have to integrate storing and readout areas in between the photo-elements. TFA (*Thin Film on ASIC*) technology overcomes this drawback with the integration of an amorphous silicon detector (a-Si:H) on top of a crystalline ASIC (*Application Specific Integrated Circuit*)[6] (fig. 1.2.2).

The layer of amorphous silicon is less than 1 μm thick and acts like a multispectral photo-diode. The maximum of the spectral response can be shifted across the visible spectrum from red on one end to blue on the other end by changing the voltage between p- and n-layer of the diode. It is the only electronic element worldwide which shows three linear-independent sensitivity peaks in the visible part of the spectrum, which are linear to the light intensity, and from which the RGB color signal can be derived. On the ASIC layer, each pixel is connected to circuitry which sequentially applies the three voltages to the diode. This way all three basic colors necessary for additive color composition are realized in one pixel and are read out one after another.

Because of the programmable ASIC, multiple readout procedures can be realized. It is possible, for example, to read only the red, blue or green part of an image, to read the RGB information of single lines or columns or predefined pixels (random access). In addition, pixels can have circuitry with functions required by the customer. In the



1.23: Photosensor in TFA-technology[6]
a) The principle of a TFA Sensor
b) The layers

most simple case it will be one or more MOS - transistors (*Metal Oxide Semiconductor*) for parallel readout or random access on pixel addresses. But also more complex functions may be integrated, so that in principle image processing algorithms like data compression or application specific intelligent procedures required by the customer can be programmed right into the ASIC.

Since all electronic circuitry is realized in the ASIC, the total sensor surface is light sensitive, which means a so-called *filling factor* of 100%. Like some of the other new camera developments TFA cameras are still under development and cannot yet be purchased. There are only a few prototypes and the future will show if they can beat the competition of the camera market.

1.2.3 Camera Lenses

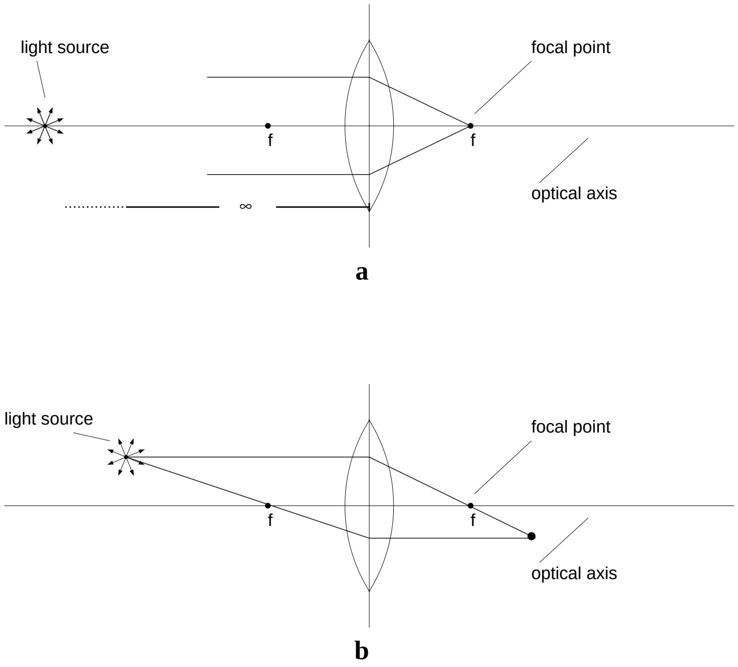
A camera lens consists of a lens system and one or more apertures. The lens system and the aperture control the amount of light which will reach the sensor as well as the depth of field. A small iris results in a large depth of field, but also causes undesired diffraction effects. A large iris results in blurred pictures when the object extends into the third dimension.

Optical Basics

An object is projected onto a sensor through an optical system consisting of mirrors and lenses. In addition there is an iris which controls the incoming amount of light and the depth of field of an image, i.e. the range in front of and behind the object, which will appear in focus.

The amount of light which passes through the lens system and ultimately reaches the sensor is proportional to the size of the aperture and the exposure time.

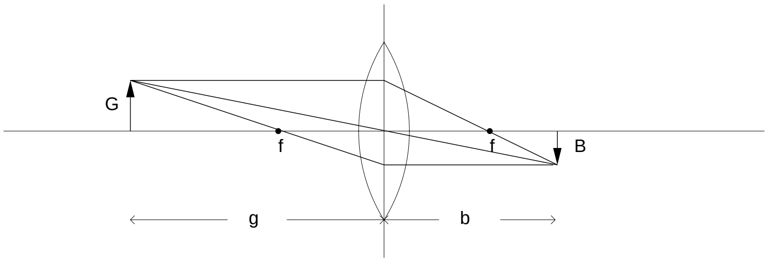
The laws in this chapter are so-called *thin lens approximations*; for thicker lenses, the formulas are much more complicated because aberrations and other lens inconsistencies influence the image depending on the thickness of the lens. But modern lens systems also incorporate several corrective lenses to eliminate geometric and chromatic distortions. Therefore, for practical purposes the assumption of thin lenses can be made in conditions where the distance of the object is at least ten times the focal length.



1.24: Imaging through a lens:

a) a light source in an infinite distance is focused on the focal point
b) if the light source moves closer, the light rays collect behind the focal point

Fig. 1.24 shows the geometric principles of a lens. Rays which originate from a light source at an infinite distance are parallel. A lens which is positioned perpendicularly to these light rays will focus them at the focal point. This means that the focal point is the image of a light source at an infinite distance. The distance between the center of the lens and the focal point is called the focal length f. This is also the distance between the lens and the CCD chip if an object in an infinite distance is to be captured. Then the chip is said to be located in the focal plane. If the light source gets moved towards the lens, the rays will be focused behind the focal point. Consequently, the distance between the lens and the CCD chip has to be enlarged. The relevant laws for thin lenses were compiled by Descartes and combined in his famous lens equations (fig. 1.25):



1.25: The optics of a thin lens

$$\frac{1}{g}+\frac{1}{b}=\frac{1}{f} \tag{1.4}$$

with
b: distance of the image
g: distance of the object
f: focal length
and

$$\frac{B}{G}=\frac{b}{g}=m \tag{1.5}$$

with
B: height of the image
G: height of the object m: aspect ratio

This indicates that focusing means simply changing the distance between the lens and the CCD chip. Obviously, however, this will eventually encounter geometric limits. Normally, a lens system allows the focusing from an infinitely distant point up to the so-called minimum object distance (MOD). the size of which follows from equation 1.4 if $b = b_{max}$ and $g = MOD$:

$$\begin{aligned}\frac{1}{b_{max}}+\frac{1}{MOD} &= \frac{1}{f}\\ \rightarrow MOD &= \frac{f\cdot b_{max}}{b_{max}-f} \qquad (1.6)\end{aligned}$$

with
b_{max}: maximum distance of the image
MOD: minimum distance of the object
f: focal length

The minimum and maximum object distance can be reduced by a spacer ring, which reduces the distance between the lens system and the camera chip.

Before a lens is purchased, an estimate of the focal length f has to be calculated, taking into account the geometric facts at the site. It can be derived from 1.4 and 1.5: 1.5:

$$\begin{aligned}f &= \frac{mg}{1+m} \qquad (1.7)\\ &= \frac{b}{1+m} \qquad (1.8)\end{aligned}$$

with
f: focal length
g: distance of the object
m: aspect ratio

Furthermore, from equations 1.4 and 1.5 one gets the useful relations:

$$\begin{aligned} b &= f(1+m) \qquad (1.9) \\ g &= f\left(1+\frac{1}{m}\right) \qquad (1.10) \end{aligned}$$

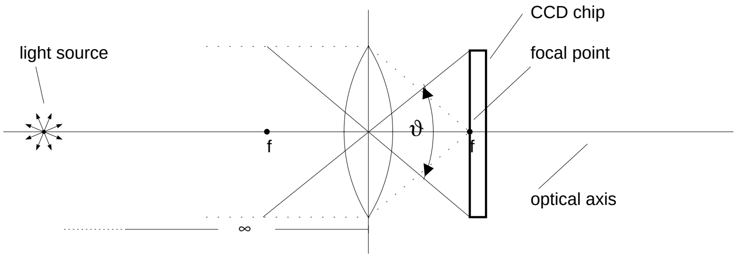
with
f: focal length
g: distance of the object
b: distance of the image
m: aspect ratio

The shorter the focal length, the greater the refractive power D of the lens. The refractive power D is the inverse of the focal length f:

$$D = \frac{1}{f} \qquad (1.11)$$

People who wear glasses are familiar with D, which is called the diopter and is measured in 1/m.

In addition to the focal length, the photographic angle ϑ is another characteristic of a lens system (fig. 1.26).



1.26: The photographic angle ϑ

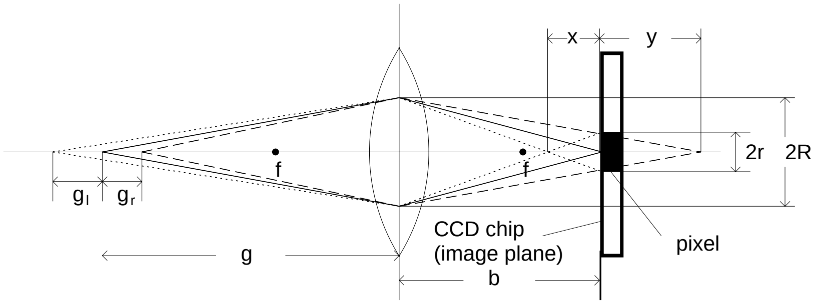
It is defined as

$$\begin{aligned} \frac{B_{max}}{2f} &= \tan\left(\frac{\vartheta}{2}\right) \\ \rightarrow \vartheta &= 2 \cdot \arctan\left(\frac{B_{max}}{2f}\right) \qquad (1.12) \end{aligned}$$

where B_{max} is the length of the diagonal of the chip in the case of area scan cameras and the width of the line in the case of line cameras. With one lens numerous photographic angles are possible, if different chip sizes are considered (tab. 1.5 p. 36).

As mentioned previously, the thicker a lens, the more the optics will differ from the above-made assumptions of a thin lens, and the greater the distortions will be. In addition, the thicker a lens, the smaller the focal length f and the larger the photographic angle. It can be calculated that with C-mount lenses, the distortions will start at a focal length of f=8 mm. This value can still be improved if highly refractive glass is used. Therefore, in metrology, C-mount lenses with focal lengths of less than 8 mm should only be used in exceptional cases since the correctional calculations which the image processing system will have to perform could be very time consuming and therefore expensive.

Another important parameter is the depth of field which has been previously mentioned. Fig. 1.27



1.27: Field of depth calculation

shows the origin of the effect. If a CCD chip shows a focused image of a point which is located at the object distance g (straight line), the image of a point which is located at g$_r$ (dashed line) or at g$_l$ (points) will be an unfocused circle. If the diameters of these two circles are smaller than the length of the edge of a pixel, any object which is located between g + g$_l$ and g - g$_r$ will be in focus. The distance

$$g + g_l - (g - g_r) = g_l + g_r \tag{1.13}$$

is called depth of field. It depends on the size of the iris of the lens along with other physical parameters. A small iris enlarges the depth of field; a larger iris makes it smaller. As you might know, photographers usually use a large iris for portrait shots in order to blur the background and to emphasize the face completely. The size of the iris is measured in f-stops k, which are well-known among photographers. In mirror reflex cameras it can be set in steps of $\sqrt{2}$: k = 0.71, 1, 1.4, 2.0, 2.8 etc. A video camera makes a continuous setting possible and the motor can be controlled by software. The f-stop is defined by the following equation:

$$k = \frac{f}{2R} \tag{1.14}$$

where f is the focal distance and R the effective radius of the iris. In the case of the combination of the iris and a thin lens, R is equal to the radius of the iris. With thicker lenses the f-stop concept does not hold, and the opening of the lens- iris system is measured by the quantity called numerical aperture N.A.:

$$N.A. = n \sin \frac{\vartheta}{2} \tag{1.15}$$

where n denotes the refractive index of the lens environment and ϑ is the photographic angle, defined in equation 1.12.

If we stick with thin lenses in this context, a small radius R of the iris amounts to a large f-stop k and vice versa. The f-stop controls the amount of light falling on the sensor (as can easily be calculated–enlarging the f-stop by a factor of $\sqrt{2}$ will reduce the area of the iris and therefore the amount of light by a factor of 2) as well as the depth of field. Camera lenses take as a measure of the light intensity the inverse of the f-stop number, the so- called *relative pupil diameter*

$$\frac{1}{k} = \frac{2R}{f} = \tag{1.16}$$

with
k: f-stop number
f: focal length
R *effektive radius* of the pupil.
If you have, for example, a 50 mm lens which has the ratio 1:2.8 imprinted on its body it means that the diameter of the pupil amounts to 50 mm/2.8 = 17,9 mm.

Descartes's lens equation applied to fig. 1.27 results in:

$$\begin{aligned} \frac{1}{g} + \frac{1}{b} &= \frac{1}{f} \text{ (see equ.1.4)} \\ \frac{1}{g + g_l} + \frac{1}{b - x} &= \frac{1}{f} \qquad (1.17) \\ \frac{1}{g - g_r} + \frac{1}{b + y} &= \frac{1}{f} \qquad (1.18) \end{aligned}$$

In addition, the following equations hold:

$$\begin{aligned} \frac{R}{b - x} &= \frac{r}{x} \qquad (1.19) \\ \frac{R}{b + y} &= \frac{r}{y} \qquad (1.20) \end{aligned}$$

from which follows

$$\begin{aligned} x &= \frac{rb}{R + r} \\ y &= \frac{rb}{R - r} \end{aligned}$$

If x and y are inserted in equations 1.17 and 1.18 and the equations are solved for g$_l$ and g$_r$ respectively, considering equations 1.4 and 1.14, the result is the range within which the object will be in sharp focus.

$$\begin{aligned} g_l &= \frac{2rkg(g-f)}{f^2-2rk(g-f)} \text{ and} \\ g_r &= \frac{2rkg(g-f)}{f^2+2rk(g-f)} \\ \rightarrow g_r+g_l &= \frac{4f^2rkg(g-f)}{f^4-4r^2k^2(g-f)^2} \end{aligned} \tag{1.21}$$

Please note that g$_r$ and g$_l$ do not have the same magnitude (fig. 1.28). From the above equations, it follows that the depth of field for a given CCD chip with a given pixel size depends on the object distance g (fig. 1.28 a), the f-stop k (fig. 1.28 b), and the focal length f (fig. 1.28 c). If the focal length f and the f-stop k are constant and the camera is moved away from the object as in fig. 1.28 a, there will come a point, when g$_l$ will reach infinity. This is the case when the denominator of equation 1.21 approaches zero, i.e. when

$$\begin{aligned} f^2 &= 2rk(g-f) \\ \rightarrow g &= \frac{f^2}{2rk}+f \end{aligned} \tag{1.22}$$

This distance is called the hyperfocal distance. Then g$_r$ is exactly $\frac{g}{2}$.

Example: The pixels of a CCD camera have a size of 16 μm $\times$ 16 μm ; the camera is equipped with a 50 mm lens, and the distance between an object and the camera is g = 1 m. The camera is set to an f-stop of k = 8. From equation 1.21 this results in a depth of field of $g_l + g_r$ = 97.5 mm. The hyperfocal distance amounts to g = 19.58 m.

Another way to express equation 1.21 can be obtained by using equations 1.4 and 1.5:

$$\begin{aligned} g_l &= \frac{2rkf(m+1)}{m(fm-2rk} \\ \text{und} & \\ g_l &= \frac{2rkf(m+1)}{m(fm+2rk} \\ \text{bzw.} & \\ g_r+g_l &= \frac{4f^2rk(m+1}{f^2m^2-4r^2k^2} \end{aligned} \tag{1.23}$$

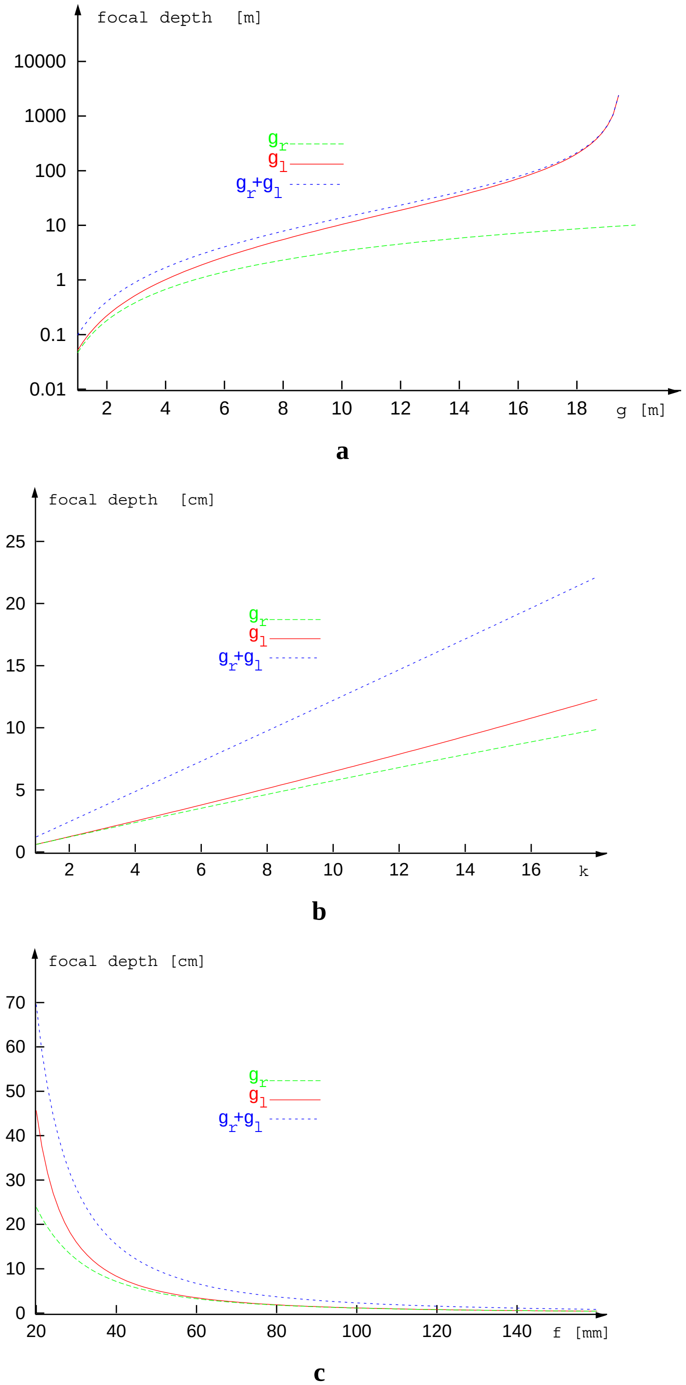
with
m: aspect ratio

The aspect ratio causing the hyperfocal case would be

$$m = \frac{2rk}{f} \tag{1.24}$$

Lens Types

Camera lenses are divided in differnt categories like wide angle lenses normal lenses and telephoto lenses. These subdivisions have historical origins, though, when cameras



1.28: The field of depth as a function of g, k and f respectively (equ. 1.21. r = 8 μm)

a) as a function of the object distance g. f = 50 mm, k = 8
b) as a function of the f-stop k. g = 1 m, f = 50 mm
c) as a function of the focal length f. k = 8, g = 1 m

used 35 mm - film. The categories would have to be modified as soon as a new CCD chip hits the market. But this, of course, is unrealistic. Instead, the terms *wide angle lens, normal lens* and *tele lens* still to this day relate to the 35 mm - film with a frame size of 24 × 36 mm. Given this frame size, the diagonal is 43.3 mm. With a photographic angle of $\vartheta = 45°$, which is roughly equivalent to the human field of vision, equation 1.12 and tab. 1.5 p. 36 yield a focal length of approximately f =50 mm. Therefore this lens is called *normal lens*. All camera lenses with a larger photographic angle are called *wide angle lenses*, and the ones with a smaller photographic angle are called *telephoto lenses*. If the CCD - camera chip is small enough, even a 50 mm - lens may have the same photographic angle as a telephoto lens. This is an important factor which has to be considered when selecting a camera lens.

Table 1.5: Photographic angles and lens names

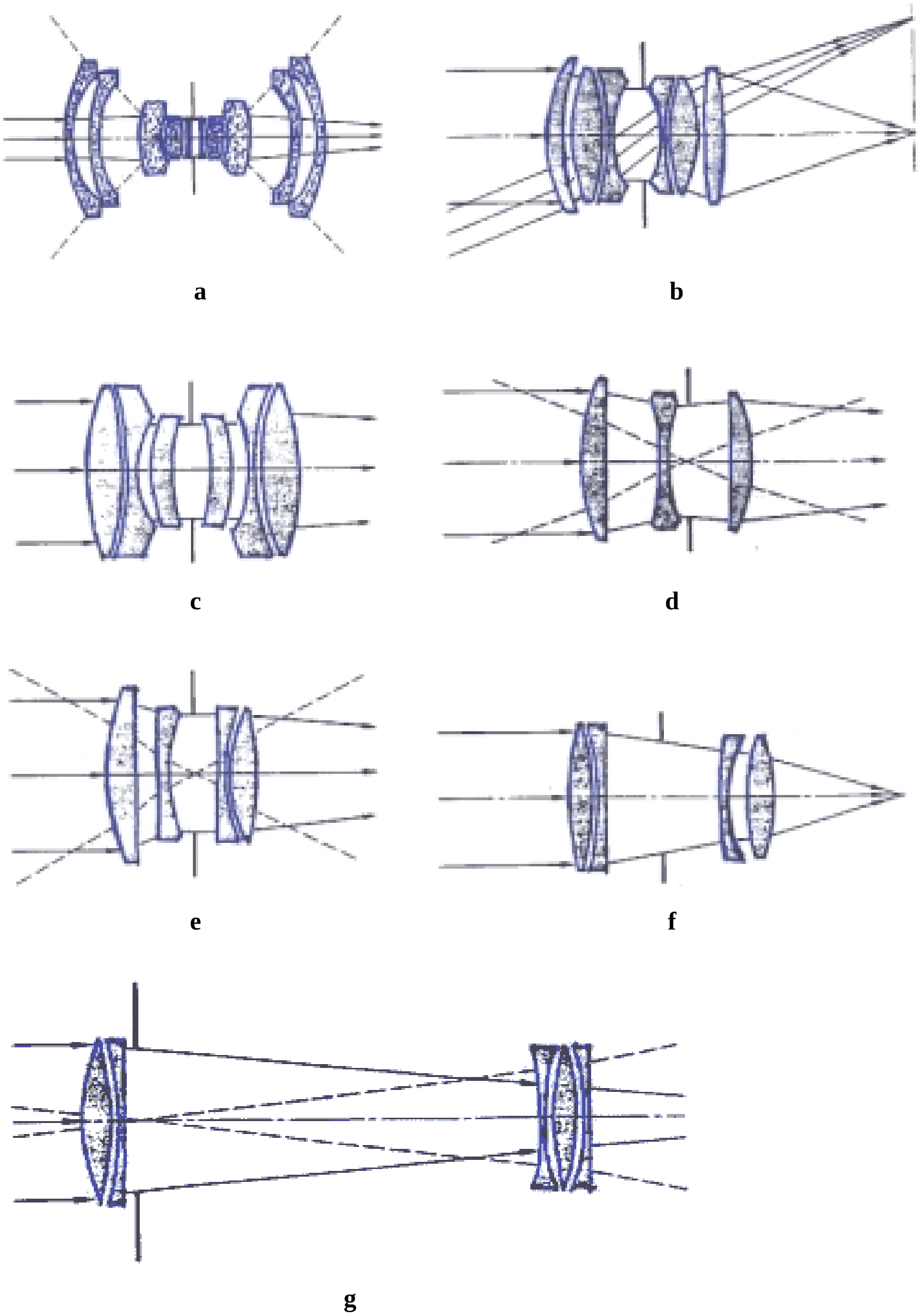
Format	24 × 36 mm	1”	2/3”	1/2”	1/3”	1/4”
Diagonal B_{max} [mm]	43.3	15.9	11.0	8.0	6.0	4.0
f = 20 mm	95°	43°	31°	23°	17°	11°
f = 24 mm	84°	37°	26°	19°	14°	10°
f = 35 mm	63°	26°	18°	13°	10°	7°
f = 50 mm (Normal)	47°	18°	13°	9°	7°	5°
f = 105 mm	23°	9°	6°	4°	3°	2°
f = 135 mm	18°	7°	5°	3°	3°	2°
f = 180 mm	14°	5°	4°	3°	2°	1°
f = 300 mm	8°	3°	2°	2°	1°	1°

Commercially available lenses incorporate lens systems for aberration corrections (fig. 1.29

- The Tessar - lens, the Gaussian twin lens, the Cooke triplett and the Petzval lens are usually constructed as 50 mm lenses
- Wide angle lenses (6 mm bis 40 mm) for example the Aviogon- or Orthogometer - lens, have smaller focal lengths and a large photographic angle.
- Telephoto lenses like the Magnar lens, have large focal lengths and a small photographic angle.
- Zoom lenses with variable focal lengths are of course the most complicated challenges in lens design.

In addition to the basic formulas derived in the previous section there are, in reality, other parameters to be considered when a lens system has to be integrated into an image processing application. Different imaging tasks require different lens types in addition to which filters and front lenses might have to be integrated.

C and CS mount lenses: C-mount and CS-mount lenses are attached to the camera body by means of a threaded connection. These two types of lenses differ only



1.29: Common lens types[19]

a) Wild Aviogon Lens
b) Gaussian Twin Lens (Biotar)
c) Zeiss Orthogometer Lens
d) Cooke (Taylor) Triplet
e) Tessar Lens
f) Petzval Lens
g) Magnar Tele lens

in the distance between the thread and the focal plane. The C-mount lens has a distance of 12.5 mm; the CS-mount lens of 17.5 mm. If a spacer ring is added to a C-mount lens, it will become a CS-mount lens. Similarly to chip formats, the origin of C mount lenses goes back to the age of tube cameras. Typical sizes are 1/3 inch, 1/2 inch, 2/3 inch, and 1 inch. In general, the format of the lens should be larger than or equal to the format of the CCD chip, so that the edge of the iris will not show up on the picture. Also, aberrations appear mostly at the edge of a lens. Consequently, a CCD chip format of, for example, 1/4 inch requires a lens format of 1/3 inch.

In addition to lenses with fixed focal lengths, manual and automatic zoom lenses are available, as are lenses on which the f-stop and focal length can be controlled by the video signal. In addition, all the lenses still available on the camera market can be used with adapters, which connect bayonet joints to C-mount joints.

Macro lenses: Macro lenses have to be used if the object is located at such a short distance from the camera that spacer rings and macro auxiliary lenses can no longer meet the requirements. This is the case when the aspect ratio m is between 0.1 and 10. They are specifically laid out for metrology, i.e. anything which might contribute to the instablility of the optical system, e.g. a changeable iris or changeable focal length is omitted. Therefore the light conditions and the mechanical setup have to meet the requirements of the macro lens. While normal lenses have the focal length as a typical parameter, macro lenses are differentiated by the aspect ratio.

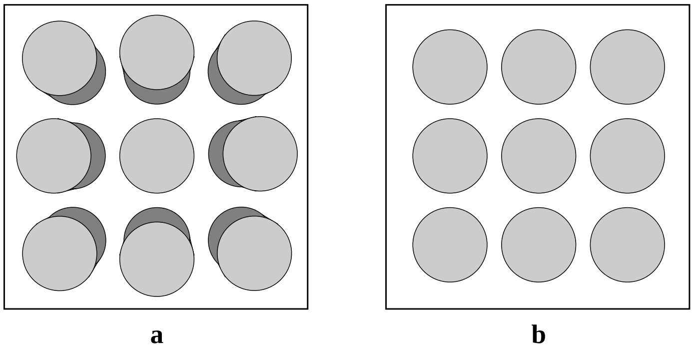
Telecentric lenses: If a three-dimensional object is photographed, the image usually also contains the depth of a scene (fig. 1.30 a)). With some tasks, however, this is undesirable. In such cases, telecentric lenses are used. They have a second small iris, which is located directly in the focal point on the opposite side of the camera body. Then only light rays which are mostly parallel to the optical axis will end up on the CCD chip, i.e. light rays coming from surfaces which are exactly perpendicular to the optical axis (fig. 1.30 b)). However, because of the small second aperture, only the light rays through the center of the lens will be captured on the sensor. Therefore only objects which are either very far away or considerably smaller than the diameter of the lens can be captured.

If the object is moved along the optical axis, the image size should not change with this type of lens but in reality, this is only possible within certain limits. Therefore, a telecentric lens has a quality parameter called the telecentric range. If the object is moved along the optical axis within the telecentric range, the image size will change less than 1 mm.

Lens Add-Ons

In addition to lenses there are various add-ons which make taking images easier.

Auxiliary lenses: Macro auxiliary lenses and filters can be attached to the lens at the opposite side of the camera body. They have the same result as the attachment of



1.30: Telecentric lenses

a) mapping through a normal lens
b) mapping with a telecentric lens

spacer rings, i.e. to lower the object distance g. They are usually attached with zoom lenses, where a spacer ring would result in mechanical instability. Fig. 1.31 explains the principle. Without a macro auxiliary lens, a point which is located at an infinite distance will be captured in the focal plane, as mentioned above (fig. 1.31 a)). If we attach a macro auxiliary lens, an object in the focal plane of that lens will have an image in the focal plane of the main lens as is shown in fig. 1.31 b). If the object is moved, an object distance g has to be set at the scale of the main lens. This scale, however, has been defined for the main lens alone, and not for a system in combination with the auxiliary lens. The new setting of the object distance g can be derived from the following formula:

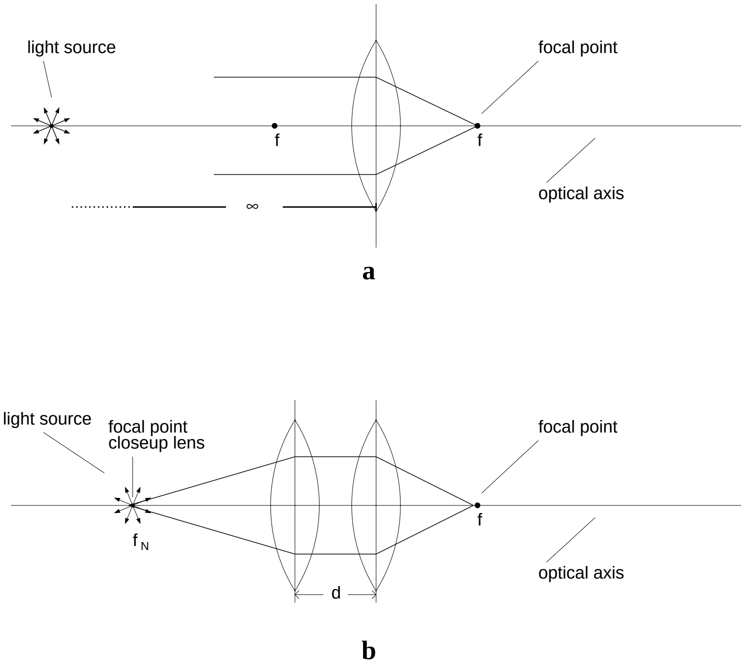
$$\frac{1}{f_{New}} = \frac{1}{f} + \frac{1}{f_N} \tag{1.25}$$

$$\frac{1}{f} = \frac{1}{b} + \frac{1}{g-d} \qquad \text{for } d << g \tag{1.26}$$

with:
f: focal distance of main lens
f_N: focal distance of auxiliary lens
f_{New}: common focal distance of main and auxiliary lens
b: distance of the image
g: distance of the object according to the scale of the main lens
d: distance between auxiliary and main lens, $d << g$
$g - d \approx g$: distance between auxiliary lens and object

From basic optics we know that the refraction power of a system of more than one lens is the sum of the refraction power of each lens. Using Descartes's lens equation, we get:

$$\begin{aligned} \frac{1}{g'} + \frac{1}{b} &= \frac{1}{f_{New}} \\ &= \frac{1}{f} + \frac{1}{f_N} \end{aligned}$$



1.31: A closeup lens and a normal lens
a) without closeup lens: parallel lightrays are focused on the focal point f
b)lightrays from the focal point of the closeup lens f $_N$ are focused on the focal point f

$$\begin{aligned}
&= \frac{1}{b} + \frac{1}{g-d} + \frac{1}{f_N} \\
\frac{1}{g-d} &= \frac{1}{g'} - \frac{1}{f_N} \\
g-d &= f_N \cdot \frac{g'}{f_N - g'} \\
&= \frac{g'}{1-g'D_N} \\
\rightarrow g &\approx \frac{g'}{1-g'D_N} \text{ for } d << g \qquad (1.27)
\end{aligned}$$

with:
g': real distance of the object
$D_N = 1/f_N$: refractive power of the auxiliary lens g: distance of the object according to the scale of the main lens.

For example, let's mount a macro auxiliary lens with a refractive power of 3 diopters. If the object has a distance from the camera of 30 cm, the scale on the main lens has to be set to 3 m.

Spacer rings: As mentioned above, the MOD can be reduced by including a spacer

1.32: Spacer rings of various sizes

ring (fig. 1.32) between the lens system and the camera body to enlarge the distance between the lens and the camera chip. However, as a result, focusing on objects at a great distance will no longer be possible–the larger the spacer ring, the smaller the minimum and maximum object distances.

Polarization filter: Polarisation filters are well-known to hobby photographers as a useful tool to prevent reflexions from shiny surfaces in a picture. Light rays which are reflected by a mirror or even a shiny surface have a certain direction of polarization, i.e. the wiggling of the light waves is limited to a a certain plane. A polarization filter which, like an auxiliary lens, is attached to the lens on the opposite side of the camera body, can be turned in a way that it will absorb the light of a certain polarization plane and therefore prevents it from getting to the CCD-chip.

Of course there are lots of add-ons on the market to treat images artistically, for example, color filters and various effect filters. However, they are beyond the frame of our interests and will not be dealt with here.

1.3 The Frame Grabber

The electical voltage signal produced by the sensor system will now be transferred to the frame grabber. The frame grabber is not identical to the graphic card in normal computers. It has to meet many more requirements.

A frame grabber should be able to

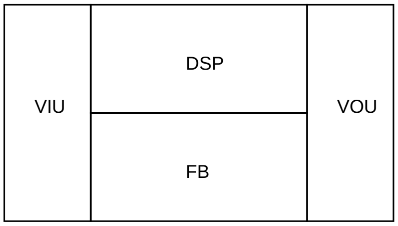
- process the information from various image sources
- store image information quickly and efficiently
- offer a graphics user interface (GUI)
- be flexible concerning various applications

Depending on the type and the price a user is willing to pay, a frame grabber might include fast DSPs with RISC architectures and multiple processor systems for parallel processing, large RAM storage capacities, sophisticated software libraries, interactive user interfaces and comfortable programming tools. Nowadays the frame grabber board is still the main component in an image processing system, although with the increasing availability of CMOS sensors, the image processing routines will be increasingly moved directly into the camera (see section 1.2.1). On the other hand, image processing algorithms can be programmed directly in the host computer. Time-critical applications, however, require a hardware frame grabber unit, either in the camera or as a hardware unit added to the host PC or workstation.

To meet the numerous requirements, most frame grabbers have a modular structure, so that the components can be configured according to the needs of the user.

Modern frame grabbers usually consist of the components (fig. 1.33):

- video input unit (VIU)
- frame buffer (FB)
- digital signal processors (DSP)
- video output unit (VOU)



1.33: Hardware components of an image processing system: video input unit(VIU), frame buffer (FB), signal processors (DSP) and video output (VOU).

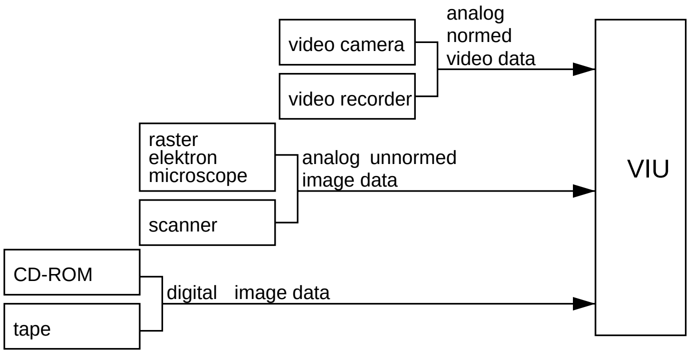
The frame buffer, as well as various digital signal processors, will be called the image processing unit. Since the market offers a very large spectrum of frame grabber types, it is difficult to describe a typical structure. The following sections can therefore only give an overwiew.

1.3.1 The Video Input Unit

The video input unit is the interface between the sensor system (i.e. a CCD camera) and the image storage unit.

Like cameras, frame grabbers offer several features which exceed the video norm. Some types can be connected to almost any signal or image source (fig. 1.34). Basically, the different kinds of data sources can be named:

- analog normed data (from video cameras, video recorders, etc.),

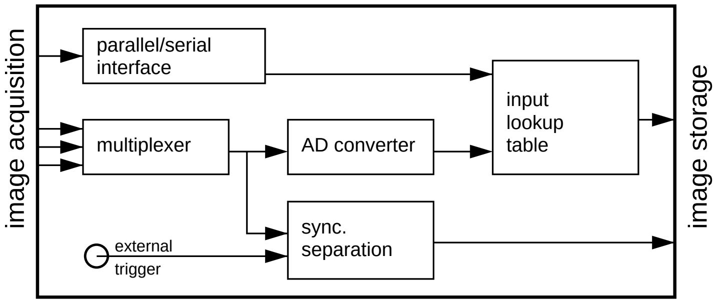


1.34: Various image and data sources

- analog unnormed data (from computer tomographs, electron microscopes, line cameras, etc.)
- digital data (from CDs, CMOS image sensors, etc.)

Because of the required flexibility, a frame grabber board has to be configurable by the user. With any of these models, the video input unit has to be able to

- multiplex the input sources
- synchronize the incoming signal with the RAM
- digitize analog data
- transfer digital data
- pre-process data



1.35: Functional units of the video input.

Therefore the following functional groups are required:

a multiplexer: Often the image information consists of multichannel video signals which are connected to the different inputs of the frame grabber board, for example the red, green and blue channels of a three chip color camera, a system of multiple black and white cameras or satellite data consisting of five and more channels.

Boards at the high end of the performance range are able to read and process all channels in parallel mode. Boards in the middle and low end of the range have a multiplexer in the entrance stage, by which a video source can be selected. The signal selection can be controlled by software. In order to be able to switch between the various video sources, they have to be externally synchronized by the PC clock or a sync generator on the frame grabber board. This unit is part of sync separation.

sync separation (also: *Sync Stripper*): According to table 1.1 video signals contain the image information plus sync signals for line start and field start. The horizontal sync signal introduces a new line; the vertical sync signal the beginning of a new field. The sync separation unit removes these two signals from the image data.

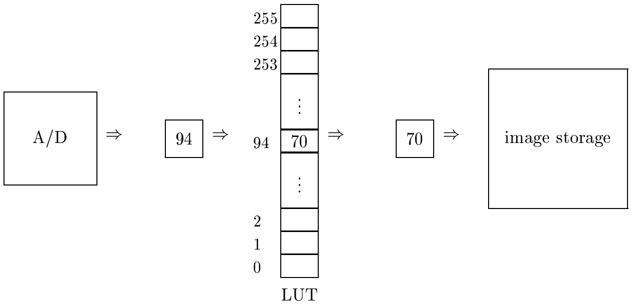
analog digital converter: The AD converter digitizes the analog input signal. The resolution of standard AD converters is 8 bit. Some boards have variable AD frequencies which can be changed by software. This makes the input of signals which do not conform to any of the video standards possible. These systems are called variable scan systems. With these systems the video input unit contains an additional trigger input (variable scan input) through which it receives the trigger signal from the video source. (fig. 1.35).

parallel and serial interface: Some images are already digitized when they reach the frame grabber board, either because the image sensor is able to produce digital data or because the data is pre- processed in the image capturing system. In such cases, the video input unit provides digital interfaces which omit the AD converter.

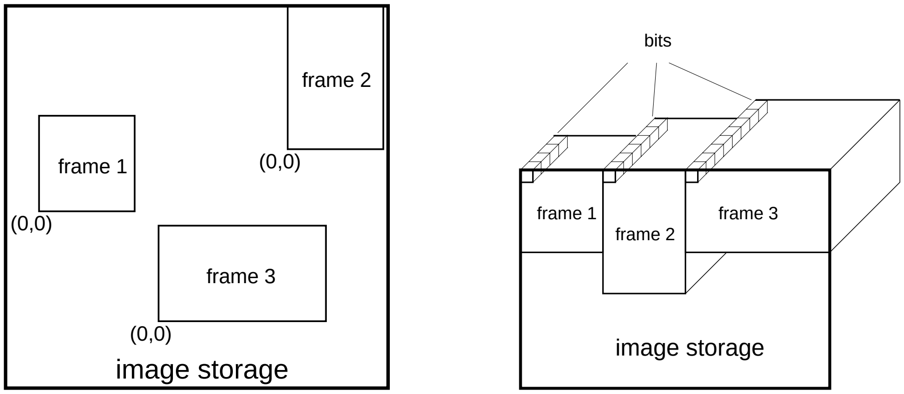
input lookup table: Before the data is transferred to the frame buffer, some boards allow the possibility of adding modifications via an electronic transformation table. Input and output lookup tables (section 1.3.4) are a number of addional memory areas. They can be accessed via the GUI and filled with numbers. The value from the AD converter is interpreted as a relative memory address. The value behind this address will then be transferred to the frame buffer (fig. 1.36). The user is able to select a lookup table in real time. This makes it possible to set a threshold or to, for example, eliminate undesired parts of an image before the data reaches the frame buffer.

1.3.2 The Frame Buffer

Data can be stored either in the frame buffer of the image processing board or in the PC's local storage. Modern PCI-bus computers provide sufficiently high data transfer



1.36: Input lookup table



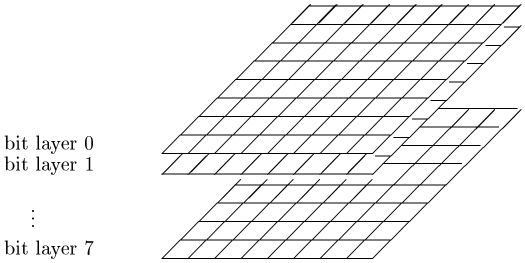
a **b**

1.37: Configuration possibilities of the frame buffer: images with different
a) sizes
b) and depths

rates to reach an acceptable processing speed. If the PC itself is equipped with sufficient storage space, it's even possible to do without the frame buffer. Indeed, in time-critical tasks, all processing steps, including the storage of the image, take place in the image processing board.

Regardless of where the frame buffer is located, it has a different administrative structure and access possibilities than normal RAM storage. While normal PC RAM is continuously addressed, with the frame buffer, the user has the impression of working on a a matrix with x- and y- coordinates. The conversion from continuous to two-dimensional addressing and to the configurations described below is peformed by the image processing system's program library.

Therefore, we define a frame buffer as a RAM area (which can be physically manifested anywhere in the system) in connection with a library, which, among other things, administers the addresses.



1.38: 8 bit-planes of a monochrome image

- It allows the possibility of configuring the frame buffer freely to store images with different sizes and depths. A frame buffer of 1 MByte can, for example, be used to store an image with dimensions of 1024 × 1024 pixels and 8 bit depth, but also for a real-color image of 3 × 512 × 512 pixels (and 512 × 512 bytes to store intermediate results). A pixel in a real-color image is addressed the same way as pixels from monochromatic images, i.e. with a storage address (x_0,y_0) although in reality it consists of three bytes (one each for R, G, and B) which might be stored physically in totally different parts of the buffer. A 1 MByte frame buffer might also be used for an image file of 512 × 1024 pixels and additional overlay levels (up to 8 bit) to display text or marks from the mouse, or to store an image sequence of 256 images, 64 × 64 pixels each. If the image processing system uses a CMOS camera (section 1.2.2) the image buffer must have a pixel depth of 20 pixels because of the large dynamic range of this camera type. The image buffer of 1 MByte will in this case be able to hold two images of 512 × 512 pixels each. However, in any of these configurations the user will want to address an image like a two- or, in the case of an image sequence, a three-dimensional matrix without having to think about pixel depth or addressing algorithms (Abb. 1.37).

- It provides several access modes. For example, an image line or column can be addressed with a single command; likewise, bit levels can be individually addressed.
- The concept of a dual-ported memory makes it possible to address the frame buffer in parallel from two sides. As a result, images can be read into the frame grabber and, at the same time, be displayed on a monitor.

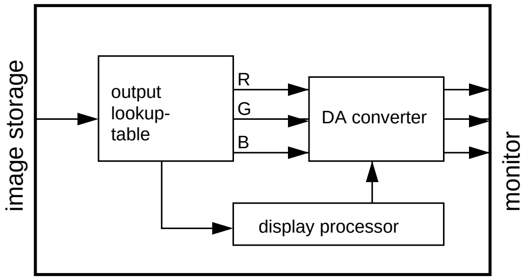
1.3.3 The Signal Processor

As mentioned previously, high end performance frame grabbers have the possibility of capturing data from various input channels in parallel. Processing this amount of data can only be performed by customized signal processors. Therefore, some frame grabbers contain one or several DSPs, for example the model TMS320C80 (Texas Instruments), which is a 32 bit DSP, to perform complex image processing algorithms like filters, convolutions, data transforms or data compression. For special tasks like neighborhood operations, specific ASIC modules can be customized. As an example, a 3 × 3 convolution of an image with 512 lines and 512 columns takes about 1.8 ms, a convolution over 5 × 5 neighborhoods of the same image will take 4.8 ms. These tasks exceed the functions of a basic frame grabber; therefore, these boards are called image processing systems. The DSPs may be located on the frame grabber board or on separate boards, which communicate via the PCI bus or internal bus systems.

Some applications even distribute the signal processors among various computer systems and are able to communicate via LANs.

1.3.4 The Video Output Unit

The video output unit of an image processing system makes it possible to display an image from the frame buffer on the screen. It has to transform the image data into



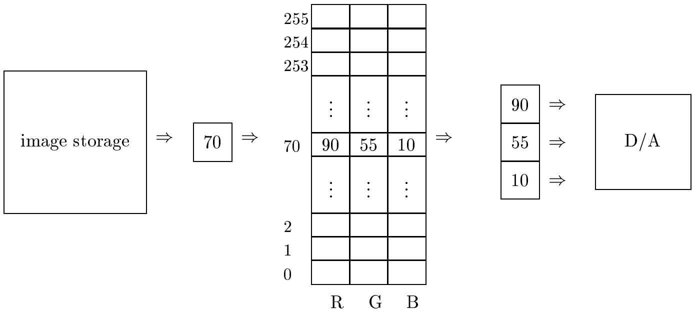
1.39: Functional units of the video output.

an adequate video signal. This means that the content of the frame buffer has to be transferred into an analog signal, which conforms to a video norm (SVGA, CCIR etc.).

The video output unit consists of two functional groups:

- the output lookup table
- the DA converter

As mentioned previously, lookup tables are memory areas which make it possible to modify pixel values deliberately. Output lookup tables generally have the same principle as input lookup tables, although an output lookup table usually has three components: a red, a green and a blue component. Therefore, any value from the frame buffer can be converted into three values which provide the three basic colors necessary for a color display of an image, although the image was originally captured by a monochrome camera. This way the values of an 8 bit pixel can be transformed into 256 colors; a pixel with more bits into respectively more colors.



1.40: Output lookup table

The digitized values from the frame buffer have to be converted into an analog signal. This is provided by the DA converter. In addition, depending on the video norm used, a certain number of pixels has to be transformed in a certain time frame. The time basis information is given by the video input unit if frames are captured and displayed under the same video norm.

New sync signals have to be generated if the input and the output video norms are not identical. Decoupling of the input and output frequencies is done via a graphic processor, which produces new horizonal and vertical sync signals as well as the scan frequency for the DA converter.

As mentioned above, images in the frame buffer can differ in width and height but also in the number of bits per pixel. This means that the image information in the frame buffer has to be transformed according to the display parameters of the video norm used. This is also done by the graphic processor.

1.4 Summary

There are numerous types of image processing systems on the market. The one described in this section is essentially the common denominator. An image processing system consists of:

an illumination unit: For most applications daylight is unsuitable. Adequate illumination saves computer time. Bad illumination often leaves irreparable artefacts in images.

a sensor unit, for example a CCD camera: The camera market is flooded with numerous models. A camera purchase should be carefully considered, with an optimal image processing system in mind.

one or more lenses, which suit the problem: The lens format has to be greater than or equal to the chip format. The use of spacer rings and closeup lenses can lead to aberrations. Telecentric lenses prevent perspective distortions.

a frame grabber board: Time-critical problems require a frame grabber board with intelligent hardware, on which fast signal processors take over most of the calculations.

suitable peripheral units for the output of results: (monitor, printer, I/O - board)

The development of image processing systems is going in a direction which will make it possible in a few years to integrate all the hard- and software into an intelligent camera with minimum dimensions.

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