OVERVIEW OF IMAGING SENSORS AND SYSTEMS USED IN BEAM INSTRUMENTATION

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Abstract

Image sensors have been in use for many years in the field of beam instrumentation. In particular cameras are widely used to take pictures of particle beams from which important parameters can be deduced. This paper will give an overview of the available image sensor technologies with particular focus to the aspects important for beam instrumentation: radiation hardness, high frame rates, fast shutters and low light intensities. The overview will also cover digital acquisition aspects including frame grabbers and digital cameras.

INTRODUCTION

The first diagnostic tool for particle beams was the fluorescent screen. Initially this diagnostics was used in conjunction with direct eye observation. The use of photographic emulsions instead of screens allowed *detailed* measurements and the first form of *post processing*.

In the fifties and sixties, with the advent of the first commercial tube cameras, it was finally possible to observe fluorescent screens remotely and continuously on TV monitors. TV based beam observation stations have been part of particle accelerators even since.

The seventies saw the rise of the integrated circuits and it became possible to "freeze" the analog video signals on external trigger events allowing the analysis of pulsed beams. Until the mid eighties however, beam imaging was used mainly as an observation tool as real measurement still required complicated and expensive systems.

The real change took place in the late eighties with the diffusion of frame grabbers and solid state cameras. At that point images of good quality could easily be digitized and PCs could be used to process the images and extract the relevant informations online. After this *revolution* the TV beam observation system became a real instrument and have been used ever since for the characterization of particle beams.

The challenge with this type of instrument is the same as that of photography as it is all about taking good images of an object. The imaging system can be divided into the following parts: subject/illumination (source in our case), optics, sensor, digitizer and post processing.

In digital photography the: optics, sensor, digitizer and post processing are usually contained in the camera itself. With automated, modern cameras, taking good quality pictures has become extremely easy. In beam instrumentation however life is not necessarily that simple. Often one has to deal with difficult light conditions: i.e. sources that are either faint or too bright, emission outside the visible range etc. Special optics may be needed to achieve the needed magnification or to adapt to space constraints requiring requiring the sensor to be installed far from the source (vacuum pipe and/or radiation). Moreover features not really useful in normal photography can be important in our applications like shutter speeds of nanoseconds or frame rates of many kilo/mega Hertz.

The most difficult problem in imaging for beam instrumentation is however the ionizing radiation. In small machines it may be possible to shield the delicate components or use optical lines to transport the light to safe rooms. In many cases, however, all this is difficult or altogether impossible and radiation hard solutions have to be found.

IMAGE SENSORS

The task of the image sensor is to convert light into electrical signals with a well defined relation between impinging light intensity and output amplitude. It should also provide information on the spatial distribution of the light on the sensor, eventually for the different colors if color imaging is required (not generally of interest in beam instrumentation.)

Types of Sensor

The most common types of image sensors are:

- CCD (Charge Coupled Device)
- CMOS (Complementary Metal Oxide Semiconductor)
- CID (Charge Injection Device)
- video tube

The CCD has been for many years the synonym of the solid state image sensor, its performance being rivalled only by recent CMOS sensors. It still has the edge in terms of sensitivity and uniformity and remains thus the standard device in astronomy. It has however lost the battle for the consumer market with CMOS already at a 90% share by volume and its destiny is to be confined to very specialized applications.

CCD

The charge coupled device was invented in 1969 by W. Boyle and E. Smith at AT&T Bell labs for which they got the Nobel prize. It is based on the Metal Oxide Semiconductor (MOS) capacitor and, although the technology

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has been refined over the last 40 years, the working principle remains the same.

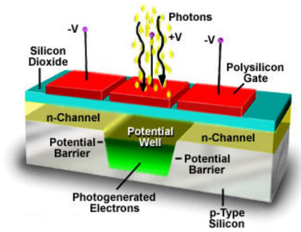

Figure 1: Structure of a CCD photo sensor based on a MOS capacitor.

Figure 1 shows the structure of a CCD photo-sensor [1]. In its simplest version it consists of a p-type-silicon epitaxial layer, an insulating oxide layer (SiO_2) and a transparent gate electrode (poly silicon). By biasing the gate with a positive voltage a potential well is created under the oxide. When the photons impinging on the surface generate hole-electron pairs the electrons are captured inside the well while the holes are pushed down into the bulk.

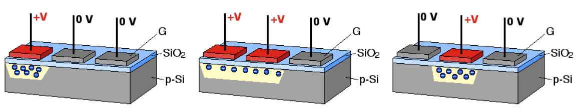

Figure 2: Shift of accumulated charge across the electrodes of a CCD.

Using a sequence of electrodes, 3 per pixel are required to keep the pixels well separated, and switching the bias from one electrode to the next it is possible to shift the collected charges from one place to another as shown in Fig. 2. Using this principle a *conveyor belt* can be created that transports the signal of each pixel from its initial position to the end of its column where it can be read out (vertical CCD). At the bottom of the CCD matrix another similar conveyor belt is placed that shifts the charges in the orthogonal direction (horizontal CCD) in order to read out all the columns using the same charge amplifier.

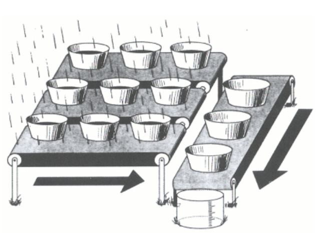

Figure 3: Integration and read-out principle of a CCD.

The mechanism is depicted in Fig. 3 [2]. In a CCD it is very important to obtain a high charge transfer efficiency (CTE) in order to ensure a uniform response across the whole area and minimize the noise. To avoid the numerous defects at the boundary between the silicon and the oxide that would reduce the CTE an n-type *buried channel* is implanted in the p silicon. This ensures that the charge is stored well below the surface at the p-n junction. The sketch of a modern CCD can be found in fig. 4 [3].

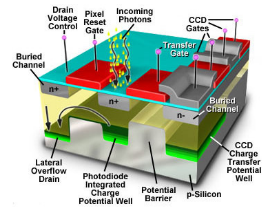

Figure 4: Anatomy of a modern CCD.

The simple CCD described above suffers from one major problem. If the light continues to arrive on the sensor while it is being read out the image will be blurred as each pixel will continue to integrate light while it moves across the sensor. The easiest solution is to use an external mechanical shutter to block the light while the image is read (Full Frame CCD). Another solution consists in doubling the number of rows and covering the bottom half of the chip with a light shield. In this case the image can be rapidly transferred from the integrating half of the CCD to the storage half and then read out at ease from there (Frame Transfer CCD). The last solution consists in covering the whole CCD matrix with a light shield and coupling each CCD pixel with a photo-sensor. At the start of the integration the photo-sensor is reset and at the end of the exposure the charge is shifted into the CCD pixel by closing the relevant gate. The CCD can then be read out without blurring problems (Interline Transfer CCD). Each one of these solutions has pros and cons. The first has the largest fill factor and thus sensitivity while the last is the cheapest to produce and provides an electronic shutter down to a few micro seconds. Figure 5 shows the layout of the three types of CCD.

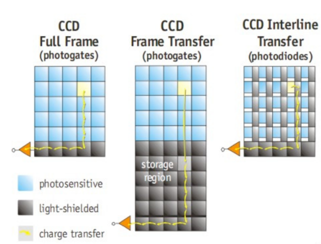

Figure 5: The three types of CCDs.

CMOS

The CMOS sensor was invented about at the same time as the CCD by P. Noble [4], but due to the technology limitations at that time it could not compete with the CCD in terms of image quality. It is in fact only recently, with the dramatic improvements in the CMOS technology driven by microprocessors design, that CMOS sensors have finally caught up with CCDs.

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Each pixel of a CMOS sensor can be individually addressed and read out. All modern CMOS sensors are based on the *active pixel* concept (APS), meaning that each pixel has it own charge amplifier (a MOS transistor in source follower configuration.) The basic active pixel design consists of one photo diode and three transistors (3T: Reset, Amplifier and Select), but high end sensors contain a pinned photo-diode and four transistors (4T: same as the 3T plus a transfer gate.) This allows the reduction of the pixel noise by mean of the double correlated sampling (DCS) explained below.

In the 3T configuration the photo-diode is inversely biased by closing the reset gate and then left floating acting as a charged capacitor. Photo-generated pairs will then discharge this capacitor proportionally to the integrated light. At the end of the integration each pixel is read out in sequence by closing the select gate and thus sending the output of the source follower to the readout bus. The disadvantage of this system is that the pixel noise is the convolution of the statistical fluctuation of the electron-hole production during integration and of the charge fluctuation during the charging of the capacitor (called reset noise). The capacity of each pixel is also different so increasing the total noise.

The dark noise of a 3T pixel is quite large (much larger than that of a CCD). In order to solve this problem a pinned-photo-diode is used to integrate the light (like in the interline transfer CCD) and a p-n junction (floating diffusion region) is used for the readout, see fig. 6. The transfer gate is normally open and before reading out the pixel the floating diffusion region is reset (charged) by means of the reset transistor with a first reading performed by closing the relevant selection transistor. The transfer gate is then closed so the charge accumulated in the pinned diode moves to the floating diffusion region (the pinning ensures that all the charge is transferred to the diffusion region). At this point the pixel is read out again and the difference between the two readings is used. Since the reset charge cancels out in the subtraction the reset noise is entirely removed. This differential technique is called correlated double sampling (CDS).

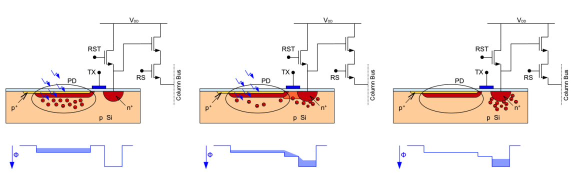

Figure 6: Signal integration and readout in a 4T CMOS.

The read-out bus is organized in columns which can be read out in parallel (1 ADC per column) or in sequence (analog multiplexer). Since CMOS sensors are implanted on standard microcircuit wafers it is possible to integrate on the same chip, next to the sensor, all the control logic and the ADCs. For this reason CMOS sensors are usually *cameras on chip*, requiring few external components and producing digital images directly.

Because of the silicon surface needed for the internal transistors, CMOS sensors usually have a rather low fill-factor. With the reduction of the feature size of CMOS circuits this problem has however been partially solved.

CID Sensors

The Charge Injection Device (CID) was invented in 1973 at General Electric and was then commercially developed by CIDTEC (now Thermo Fisher Scientific). The CID is somehow in-between a CCD and a CMOS. The photo-charge is collected under a photo-gate like for the full frame CCD while the sensing is done at pixel level like for a CMOS using a very similar addressing/amplification architecture. Fig. 7 shows a sketch of a CID active pixel.

In the case of the CID the read-out procedure is non destructive, meaning that after reading the integrated charge value it is possible to continue the integration without any signal degradation. This feature is exploited in high dynamic range cameras where each pixel is reset at different rates depending on how fast it fills up.

Another advantage of CID sensors is their radiation hardness (up to about 5 MRad). This is achieved by tuning the design and by using only p-type silicon for the sensitive areas (as explained later).

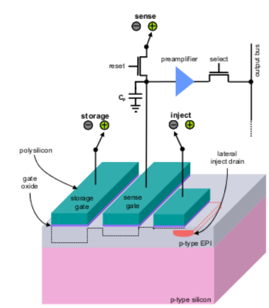

Figure 7: Sketch of a CID pixel.

Video Tubes

Video tubes were the first type of electronic imaging sensors. They are now obsolete as they can not compete with solid state devices in any aspect. Production still continues for special applications, but they will soon become a relic of the past.

Light Absorption in Silicon

The light absorption length of silicon ranges between about 0.1 μm at 400 nm and 10 μm at 800 nm as can be seen in fig. 8. For image sensors this has an important impact as it affects the sensitivity. For short wavelengths, below 400 nm, the photons are absorbed in the poly-silicon electrodes or in the insensitive surface layers while for long wavelengths only a small fraction is absorbed in the depleted layer (typically less than 10 micrometers)

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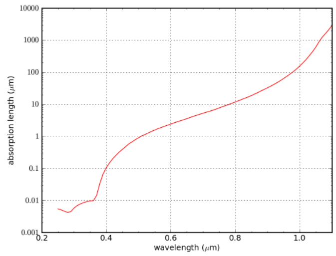

Figure 8: Light absorption in silicon vs. wavelength.

The range of the sensor can be extended by eliminating the insensitive layer near the surface and by using thick charge collection layers. Usually both improvements are obtained using back illuminated sensors. In these sensors the extra silicon of the bulk is removed by etching or grinding and the light impinges on the back side. Another advantage of back illuminated sensors is that the full pixel area is sensitive since the required metallizations and circuits are on the opposite side. The disadvantage of this technique is that global shutter devices (see below) are difficult/impossible to obtain. Figure 9 shows the structure of back and front illuminated CMOS sensors (similar solutions exist for CCDs). Back thinning together with CDS allows the CMOS technology to compete with CCDs in most fields.

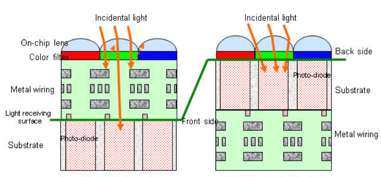

Figure 9: Structures of front and back illuminated CMOS sensors. Micro-lenses are also applied to concentrate the photons on the active area of the pixels.

Global vs. Rolling Shutter

Image sensors can have different integration-read-out sequences. The two most important are known as *global shutter* and *rolling shutter*. In a global shutter all pixels are exposed over the same time interval and is the default method for CCDs. In a rolling shutter each pixel integrates from one read-out to the next and since the pixels are read out sequentially, there is a small delay from pixel to pixel. The exposure delay from the first to the last pixel equals the time needed to read out the frame.

CMOS and CID sensors natively use the rolling shutter. Global shutter CMOS exist ($\geq$4T), but usually have higher read-out noise as the CDS can not be used since the transfer gate is pulsed together for all pixels at the end of the exposure and the floating diffusion region is used to store the charge until the pixel is read out.

The rolling shutter can introduce artefacts in case of fast moving objects as can be seen in fig. 10.

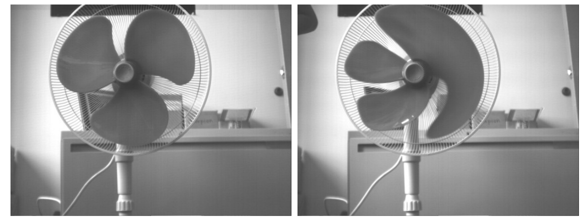

Figure 10: Images of a turning fan taken with a global shutter *left* and rolling shutter *right*.

In many applications, where an external mechanical shutter is used, this effect can be neglected. In the field of beam diagnostics however, with the pulsed nature of our sources, care should be taken with the shutter mechanism used.

Performance of Solid State Imagers

Dramatic improvements have been made in this field over the last 40 years in terms of performance, cost and size. Recent years have seen the CMOS technology overtake the CCD in all but very specialized areas and the improvements are still progressing. The best sensors today have readout noise of one or less electrons (cooled), dynamic ranges of more than 80 dB and quantum efficiencies above 70%. Standard consumer sensors (not cooled) have read-out noise around 10 e^-, dynamic ranges of about 60 dB and quantum efficiencies around 30% (meaning read-out noise of about 30 photons/pixel).

CID radiation hardened cameras have a lower performance with about a factor 5 larger read-out noise than standard CCDs.

IMAGE INTENSIFIERS

Image intensifier tubes (II) have been around for many years, initially they consisted of a photo-cathode, an accelerating and focusing electrostatic system and a phosphor screen (GEN-0). The gain and resolution of these devices was limited. Later multi channel plates (MCP) were added in-between the photo-cathode and the phosphor screen increasing the amplification by up to 10^6. Several MCPs can be stacked together to boost the gain at the expenses of the spatial resolution. In modern devices the electrostatic focusing has been replaced by proximity focusing (i.e. by reducing the drift space to sub millimetre level). The sensitivity of the image intensifiers has also been increased by the introduction of better photo-cathodes. Figure 11 depicts different configurations of GEN-3 image intensifiers while fig. 12 shows the spatial resolution for the different types.

Image intensifiers are not only used in low illumination conditions (they can detect single photons), but also where fast gating is required. By pulsing the cathode bias voltage or by introducing a control grid near the photo-cathode it is

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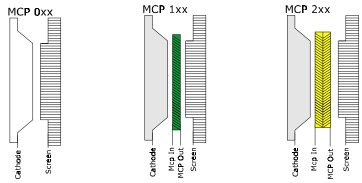

Figure 11: Layout of image intensifiers with 0, 1 and 2 MCPs.

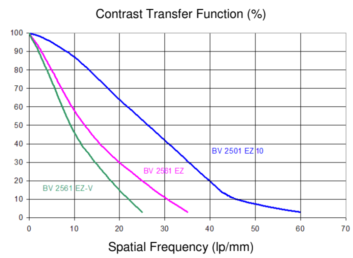

Figure 12: Spatial resolution of different image intensifier configurations: 2 MCPs *green*, 1 MCP *pink* and no MCP *blue*.

possible to gate the transit of the photo-electrons from the cathode to the anode (or to the MCPs) and thus obtain the effect of a fast shutter. Gate pulses of a few nano seconds are possible with this technique.

The spatial resolution of image intensifiers (usually expressed in lines per millimetre) is not very good if compared to image sensors. To reduce this effect large area image intensifiers are used (the resolution is not influenced by the size) which are then coupled to the sensor by a de-magnifying optics (fibre taper or relay lens). This solution has the unfortunate side effect of reducing the coupling efficiency.

RADIATION IN MOS

Ionizing radiation has a negative effect on most materials and image sensors are not spared from it. There are several mechanism that deteriorate the sensor performance after being irradiated, the most important are: flat band shift, de-passivation of the interface layer and dislocations with creation of traps.

Flat Band Shift

When an ionizing particle crosses the dielectric layer of a MOS device it creates electron-hole pairs. The charges then move under the effect of the gate's electric field and while the electrons are drained away either at the electrode or at the silicon side, the holes will remain trapped near the interface between the oxide and the silicon (or the gate depending on the polarity of the voltage). In case of positive bias the holes trapped at the oxide-silicon interface will modify the potential well under the gate and thus perturb the functioning of the CCD [5].

The effect of flat band shift can be compensated by increasing the voltage used to bias the gates, this has however side effects and can only be done inside certain limits.

The flat band shift is much more important in CCDs than in CMOS sensors since the oxide layer in the former is much larger (about 20 times, 80 nm and 5 nm respectively). In fact modern CMOS technology (not yet used for imagers) has reduced the thickness of the oxide layer by so much that quantum tunneling can evacuate the accumulated charges.

In case of mixtures of silicon-oxide and silicon-nitride, often used in the production CCDs, the flat band shift problem is more complicated (electron-hole mobility in silicon-nitride is almost zero) and can bring beneficial effects.

De-Passivation of the Interface Layer

The silicon and silicon-oxide lattices have different sizes, which means that at the interface between the two a lot of defects (traps) exist. It was discovered that the density of these traps can be reduced by annealing the processed wafers at high temperature in an H_2 atmosphere. The ionizing radiation has the effect of reversing this passivation mechanism, increasing the number of traps at the interface between silicon and the oxide and, as a consequence, increasing the dark current.

Dislocations and Trap Creation

Ionizing radiation can also dislodge some atoms from their position inside the lattice creating a vacancy-interstitial pair. Vacancies have a rather large mobility in silicon and can eventually recombine with an interstitial. If the vacancy encounters an oxygen or phosphorus atom however it will form a stable bond creating a trap. Since phosphorus is used to dope the n-silicon, vacancy-P traps are more likely in this type of silicon and thus in the n-channel of the typical CCD. The effect of the traps is twofold: they increase the dark current of the pixels and they reduce the CTE also creating smear by trapping/releasing charges with a delay during the read-out process. Clearly the CTE is only important for CCDs so CMOS sensors are less perturbed by this effect.

The effect of traps on the overall performance of a device depends on the temperature. Cooling the sensor will reduce their negative effects.

One option for hardening a CCD consists of replacing the n-channel with a p-channel (the P doping concentration in the n-bulk is quite low). CCDs based on p-channels have been fabricated and positive effects have been observed. The design is however more complicated and several compromises have to be made [6].

Radiation Hard Cameras

Several radiation hardened sensors have been developed for space applications in the past and the field is undergoing constant progress. Unfortunately most of these developments do not really suit the requirements of beam diagnostics as the needs in imaging for astronomy are quite different from ours. It is nevertheless important to keep an eye on the progress.

Few commercial rad-hard cameras exist on the market, with those available based on video tubes targeting the nuclear power industry. The market is however shrinking and these devices become more difficult to find and more expensive.

Thermo Fisher Scientific provides solid state cameras, based on CID sensors, that have relatively high radiation tolerance (up to 5 MRad for gamma radiation). Although the characteristics of these cameras can not match those of CCD or CMOS based cameras, in many cases they may fulfil the requirements of a diagnostic device. At any rate the image quality of a CID camera is far better than the quality of a radiation hard tube based camera.

For what concerns tube cameras there is no real radiation limit, at least for VIDICON tubes. Other target material may result in higher sensitivity to radiation. The limit for these cameras is given by the browning of the optics and the physical integrity of cables and wires. On the other hand the video tube has a limited lifetime intrinsically, independent of the accumulated dose.

FAST IMAGING

In some applications there is the need to acquire a sequence of images at a very high rate in order to capture transients. For example in the observation of the beam distribution turn after turn or bunch after bunch.

High Speed Cameras

High speed cameras exist on the marked that may be suitable in certain cases. This type of device is usually used in car crash tests or in ballistic studies. These cameras are composed of a sensor (or a mosaic of sensors to increase the readout rate), a fast local memory to store the sequence and a control unit that synchronizes the acquisition and connects the camera to the external world. The sensors are always CMOS and as a consequence it is possible to read out small areas of the sensor (Area Of Interest, AOI) at speeds much higher than the full frame speed. In order to achieve the high read-out rate these sensors have to make many compromises in terms of image quality and noise. The sensitivity of high speed sensors is usually 5 to 10 times lower than normal sensors. Coupling to image intensifiers is possible to overcome this limitation, but the decay time of the phosphor has to be taken into account.

Frame rates up to 10^5 frames per second (fps) are possible with this type of devices, with rates up to 10^6 fps for very small AOI. In comparison standard CMOS sensors can reach 100 fps while CCDs usually stay below 50 fps.

High speed cameras are very delicate and expensive objects (∼100 k$) not suitable for ionizing radiation environments. Their use is therefore limited to situations where the camera can be installed in a safe room or where the radiation is very low. Even for short tests, with negligible integrated dose, it may be difficult to use these devices in the presence of radiation due to the high sensitivity to single event upsets (SEU).

High Speed Profiles

In many cases what is needed are simply the transverse beam profiles, which are usually computed from the images. It is possible to acquire profiles directly at high speed by using linear image sensors, both CCD and CMOS types exist. With these rather inexpensive devices it is possible to acquire profiles up to 10^5 lines/s. The draw back is that a complex optics system has to be used to squeeze the image into a line. This can be achieved either using cylindrical lenses, as in the case of the LHC matching monitors [7] shown in Fig. 13, or using light guides.

A variant to the linear sensor consists of using multi anode photomultiplier arrays (Hamamatsu offers a 32 channel device) or pixelated SiPMTs (custom devices with 128 pixels on a single line have been produced for the LHC experiments). These devices provide parallel outputs so that each channel can be read out separately at rates of hundreds of MHz offering at the same time single photon sensitivity.

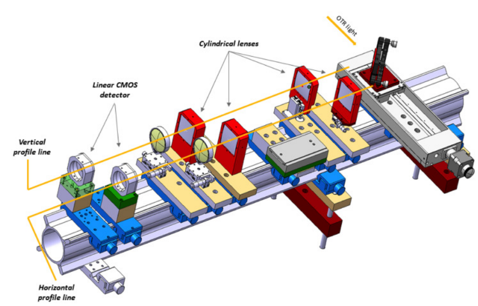

Figure 13: Rendering of the optical bench used for the LHC matching monitor.

IMAGE ACQUISITION OPTIONS

There are three main ways of acquiring digital images. The first consists in connecting an analog camera to a frame grabber. This was the most popular solution until a few years ago. The second consists in using a digital camera connected to a special interface board and using dedicated communication protocols (like camera-link). This solution was often used for scientific cameras or special applications in the past. The third option consists of using a digital camera connected to a computer via a standard bus (gigabit-ethernet, USB, firewire etc.). The third way is by far the most popular nowadays and all other techniques are only retained for special cases or in old systems.

In terms of image quality, the earlier the digitization takes place the lower the noise usually is. For this reason digital cameras have much better performance than analog

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cameras even when based on the same image sensor. The transport of a digital signal is also usually much cheaper than the analog counterpart and using optical fibres can extend for kilometres without any degradation. On the other hand, in our trade, digital cameras mean more electronics in the hostile environment (radiation). The best compromise should therefore be identified on a case by case basis.

With analog cameras the video signal is standardised in order to allow any camera to be connected to any video equipment (of the same standard: CCIR, RS-170 etc.). This allows large flexibility in the selection of the components of an imaging system and obsolete parts can easily be replaced with new components.

With the advent of digital cameras the need for a standardisation has faded and it is now possible to find hundreds of different combinations of resolutions/bus/protocols. To some extent this is an advantage as it is always possible to find a product well suited for each case. On the other hand it poses a problem of maintainability for large scale systems.

Imagine a system with hundreds of cameras. In the analog case many different brands/models can be installed in parallel and it is possible to interchange any of those without major reconfigurations of the acquisition chain. In the digital case, the replacement of a camera by a different model usually requires substantial software modifications in the control system. Moreover the communication/control protocol of digital cameras is usually proprietary making the integration in existing control systems difficult.

Considering that in the case of beam instrumentation cameras are often consumable items (lifetime of few years due to radiation) and that the market lifetime of electronic products is also of only a few years, with digital cameras one may end up having to constantly adapt the system and being tied to a specific brand.

On the other hand it is important to note that analog cameras are becoming obsolete and may become difficult to find in the future. Analog frame grabbers are already starting to disappear, but an easy solution can be found with modern ADC/FPGA boards. The transition from analog to digital goes hand in hand with the transition from CCD to CMOS sensors, the first being analog by design, the second digital for performance reasons.

IMAGE ANALYSIS

In beam diagnostics images need to be analysed in order to extract the useful information. The first step usually consist in eliminating the unwanted features from the image like: background noise, reflections and fixed patterns. The geometric distortions introduced by the optics are then corrected (rotation, trapeze, pin-cushion etc.). Non linearities of the sensor or of the optics should also be removed. Finally the processed beam image can be analysed, in most cases this means calculating and fitting the projections or using muti-dimensional fits to fit the whole image. The interesting parameters are usually the position and width of the beam spot, but in certain cases this can be much more complicated like in the case of pepper pot screens.

Unfortunately in this field every group tends to reinvent all the tools from scratch every time. In part this behaviour is justified by the different needs and the different environment used at the different laboratories, but these developments have much more in common than in what they differ.

Indeed the effort to integrate an existing tool in a control system may look as large as developing from scratch. In reality the initial coding is only a small part of the whole effort as all the operations have to be debugged and validated. It is not infrequent that years later mistakes are discovered which introduced errors in the measurement. The problem is very similar to the case of numerical computation where code reuse is a rule and where aged FORTRAN routines are still used in modern programs to avoid bugs which may be introduced by recoding.

A collaborative development of software image analysis tools for beam instrumentation would certainly be beneficial for every laboratory.

CONCLUSIONS

A panorama of the imaging technologies and market trends of today has been given. On the image quality side the market is evolving fast and in the right direction. Unfortunately our main concern if often the ionizing radiation which conflicts with the present trend of encapsulating ever more functions inside the camera heads and in the image sensors themselves. It may not be long before we have to produce our own image sensors, for example to replace obsolete tube cameras.

Imaging for beam instrumentation is a field where a more solid collaboration between laboratories could bring large benefits in terms of results and resources.

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