Linejitter and Geometric Calibration of CCD - Cameras

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Abstract

Precise radiometric and geometric transmission of images from CCD-sensor to memory is a fundamental aspect of CCD-camera calibration. Linejitter and other degradations occuring during transmission are major limiting factors of the precision attainable with most current CCD-cameras and framegrabbers. The video signal, synchronisation signals and principal electronic components involved in synchronisation and transmission are analysed and their influence on linejitter discussed. A method for signal transmission with the elimination of linejitter and other degradations is shown. Methods for the determination and correction of linejitter are discussed.

1. Introduction

The geometric uniformity of CCD-sensors, if disregarding problems of flatness, can be better than 0.01 of pixel spacing, as indicated by uniformity of litographic processes, investigations of sensitivity and noise and with interferometric techniques. Well defined features of interest, such as points and lines, can be located in digital images with a precision of 0.01 of pixel spacing using template matching.

In tests with a three dimensional testfield, off-the-shelf CCD-camera and framegrabber, accuracies of 0.05 of pixel spacing in x and 0.02 in y (x in row direction, y in column direction) were confirmed with checkpoints *(Beyer 1987)*. The level of accuracy achieved and the difference of accuracy between the two sensor axes of a factor 2.5 indicate, that the uniformity of the sensor geometry can quite well be exploited in y-direction, but is not achieved in x-direction. Similar nonuniformities are also apparent in analysis of temperature influences on the location of targets ("warm-up effects"), where drifts in x are of up to 10 times larger than in y *(Dähler 1987)*.

These phenomena must be attributed to geometric and/or radiometric degradations incurred during the transmission of the "image" from sensor to memory. Most systems are (still) using television signals for the information transfer from camera to framegrabber as well as for their synchronisation. The signals and electronic elements involved in synchronisation and signal transmission must be investigated, sources of degradations localised and possible enhancements for reduction or elimination of degrading influences evaluated. Methods for the detection and correction need to be analysed with respect to accuracy, speed and applicability to actual measurement tasks. Methods for the detection and compensation of linejitter can also be used for images grabbed from still video systems and video tape recorders, where methods for the electronic elimination cannot be expected in the near future.

2. Synchronisation and Transmission with Video

Synchronisation and data transmission with analog signals (video) requires that a certain amount of information is transmitted such that a receiver can either synchronise (as required for example among cameras, or flash lights and cameras) or receive the pictorial data. The information required for a complete transmission is:

1 analog data (video)
2 zero reference and range reference of analog data (black and peak white reference)
3 sampling times (pixelclock)
4 start of a new line (horizontal synchronisation)
5 start of a new field/frame (vertical synchronisation)
6 if interlaced, an indication of first and second field

Specification of voltage levels, impedance and polarity of signals are required for the design of electronic elements. From this information a receiver can reconstruct thru digitisation the original image, irrespective of the number of pixels per line, lines per field, fields per frame and radiometric level and range. Some signals are analysed in the following.

2.1. The Composite Video Signal

The timing characteristics and voltage levels of composite video signals are defined in standards such as RS-170 (USA and Japan) and CCIR (Europe and Australasia), representing the two major ones for monochrome video signals. Both were drawn up in the late 1950's for use in broadcasting, thus they had to meet quality criteria for visual observation and were made to suit monitor circuitry available at that time. They differ with respect to timing characteristics such as frames per second, number of lines per field, etc., but use identical principles. The following discussion can thus be restricted to the CCIR standard.

A frame (image) consists of two fields which are transmitted consecutively 50 times per second. They are displayed in an interlaced way, meaning that consecutive lines of a frame are from two different fields. As schematically depicted in Figure 1, the first field contains the lines 2, 4, 6, etc., ending with a half line, whereas the second field starts with a half line and continues with the lines 3, 5, 7, etc..

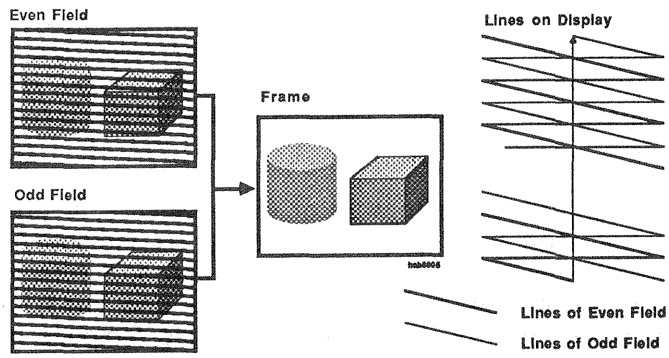

Figure 1: Frame, fields and lines in interlaced video

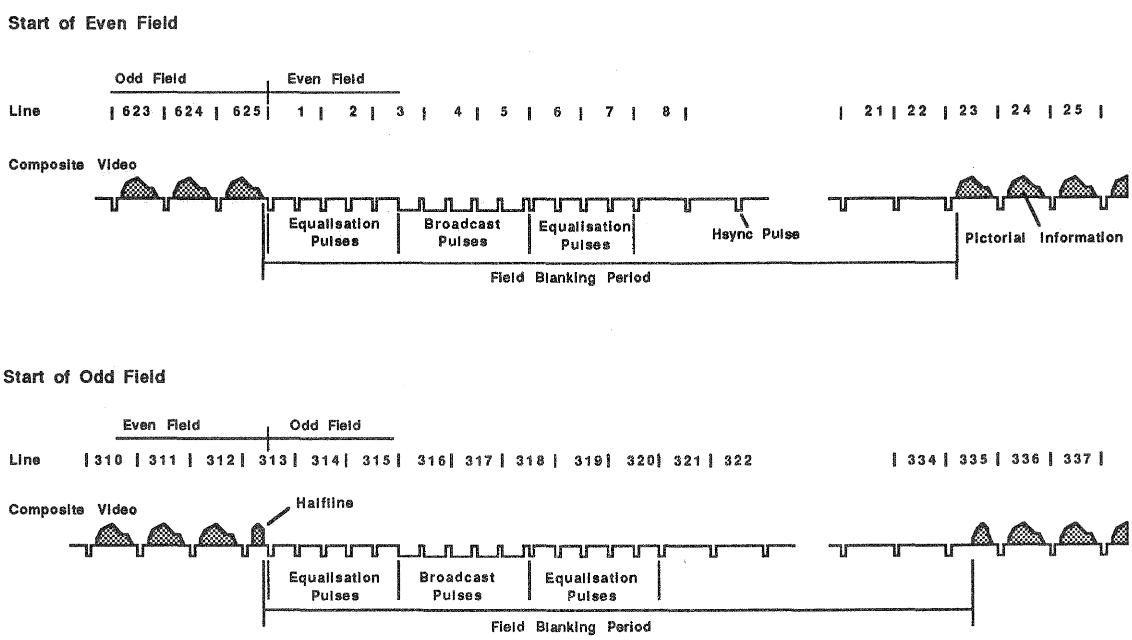

Figure 2: The CCIR video signal

The start of each field is indicated by a vertical synchronisation signal (field sync, vertical sync, vsync). Figure 2 shows the composite video signal with synchronisation signals and pictorial information. There are 22 hsync periods at the start of fields, called the vertical blanking or field blanking period, during which equalisation pulses, broadcast pulses and lines without pictorial information are transmitted. Equalisation and broadcast pulses are used to perform the vertical retrace on video monitors and the latter indicate the vsync for framegrabbers. The period from vsync to vsync is 312.5 hsync periods or 20 msec.

Lines of video data are separated by the horizontal blanking period, which consists of a front porch, a line sync pulse and a back porch (see Figure 3). The start of a line (row of an image) is referenced to a level on the falling edge of the line sync pulse, called line synchronisation signal (line sync, horizontal sync, hsync), defined by the falling edge of the line sync pulse. This edge is not sharp and requires precise level detection and signal stability for horizontal synchronisation.

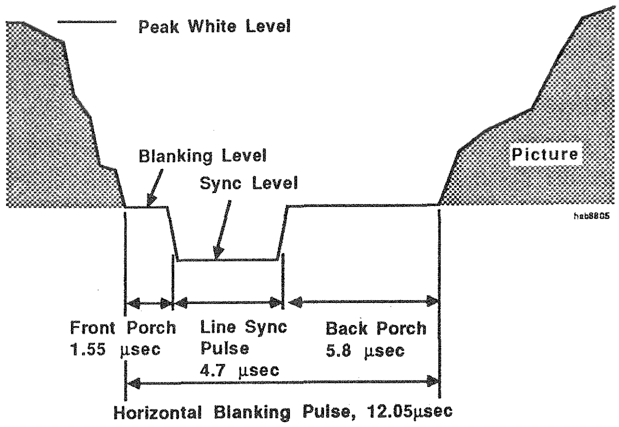

Figure 3: The CCIR video signal: horizontal synchronisation pulse

The timing signals incorporated in the composite video define the geometric properties of image transmission. The origin of the y-axis for each field (when using an image coordinate system with x in row and y in column direction) is given by the vsync for that particular field. The spacing (scale) is defined by the steps from line to line. Errors in the detection of vsync have no influence as long as they are smaller than one line time, which is usually the case.

Similarly on each line the origin of the x-axis is defined by the hsync signal for that line. The scale is not explicitly transmitted and can either be determined from the time between hsync to hsync and a certain number of pixel periods that should occur during this time, or by assuming some pixelclock period. The detection of hsync and the lack of a transmitted scale reference is the origin of linejitter and scale uncertainties that will be discussed in more detail later on.

The radiometric properties of an image are encoded as voltages with respect to the blanking level. Any error in the detection of this reference on the backporch shifts the graylevel of the following row. The lack of a peak white reference for the definition of the range requires an exact calibration of transmitter and receiver with respect to this range, on the other hand providing for analog offset and gain (amplification).

Disadvantages of the composite video signal for precise image transmission are:

- Consecutive lines are transmitted in different fields (interlacing).
  For a given degree of geometric and radiometric uniformity from row to row, better longterm stabilities of horizontal synchronisation and level detection are required. Adjacent rows are imaged 1/50 sec apart. Memories require addressing hardware to map interlaced data to noninterlaced (linear) memory. Only frame-transfer CCD-sensors can take good advantage of interlacing, whereas interline and CID-sensors require different sensor elements.
- Only 290 full lines of pictorial information are transmitted per field (half lines are rather useless for CCD-sensors and any kind of processing), resulting in 580 lines per frame. This makes it unsuitable for any large sensor array.
- No scale in x is explicitly transmitted, leading to an origin and scale uncertainty.

- The synchronisation signals, which themselves carry a certain amount of imprecicion, must be separated from video information at the receiver, thereby introducing additional uncertainties from sensing electronic elements.
- The radiometric reproduction depends on the relative calibration of the transmitter and the receiver as well as on assumptions on a maximum level above a reference.

Advantages of the composite video signal are:
- It is an accepted and widely used standard.
- It is widely used in broadcasting and consumer electronics, driving new developments and reducing equipment prices.
- Only one transmission cable (plus shielding) is needed.

2.2. Other Synchronisation Signals

Other signals used are composite sync, vertical sync, horizontal sync and pixelclock. Composite sync has identical synchronisation signals as composite video (standard video signal), but contains no video data (pictorial information). The vsync signal has, in CCIR, a period of 20 msec corresponding to 312.5 hsync periods, hsync one of 64 μsec. Both are rectangular periodic signals and have, depending on the implementation, different reference levels, impedances, high/low ratios and polarity. The pixelclock is a signal with a period corresponding to the one of pixels on the analog signal and a constant phase shift. This signal can define the clock rate of another camera or the sampling interval of the A/D converter. With an accurate pixelclock the scale between sensor and memory can be made identical, providing for a precise geometrical transmission. Linejitter, as well as many temperature effects, can be eliminated. It is possible to encode the hsync, vsync and other information into the pixelclock as well as to send it only during active data. This requires that manufacturers of cameras and framegrabbers establish standards and/or protocols to be used. Currently it requires very flexible framegrabbers to be adaptable to various cameras and vice versa.

3. Image Transmission and Frame Grabbing

Synchronisation is relevant to transmitter(s) and receiver(s). A master transmitter can run independently and generate timing that can subsequently be used by one or more slave receivers. Slave transmitters are, on one hand receivers and must thus lock on to a given timing, on the other hand transmitters sending timing signals. A complete discussion of all possibilities of synchronisation and data transmission would surpass the scope of this paper. The geometric performance of a master camera and a slave framegrabber shall be evaluated with the following signals used for synchronisation and transmission:
- composite video
- video plus hsync and vsync signals
- any of above plus pixelclock

Before analysing the characteristics of framegrabbers it is necessary to note a particular characteristic of video signals from CCD-cameras. The charge to voltage conversion at the sensor readout register produces a signal with a voltage peak for each pixel. Although these peaks are reduced by sample and hold and/or low pass filters the video signal often still exhibits part of these peaks.
When sampling by the A/D converter is performed with a period differing from pixelclock, phase patterns will appear in the digital image (see Figure 4). To exclude these phase patterns it is necessary to perform appropriate low pass filtering of the analog signal before the A/D conversion. Most frame grabbers use filters with a cutoff frequency of 3 to 5 MHz, which unfortunately often exhibit asymmetric characteristics introducing significant distortions. The filtering is generally not perfect and some phase pattern remains (which can be used as a method for detection of linejitter). For optimum digitisation it is necessary to sample with the pixelclock period phased correctly to the peaks on the video signal (oversampling is usually not a realistic option, due to the frequencies required).

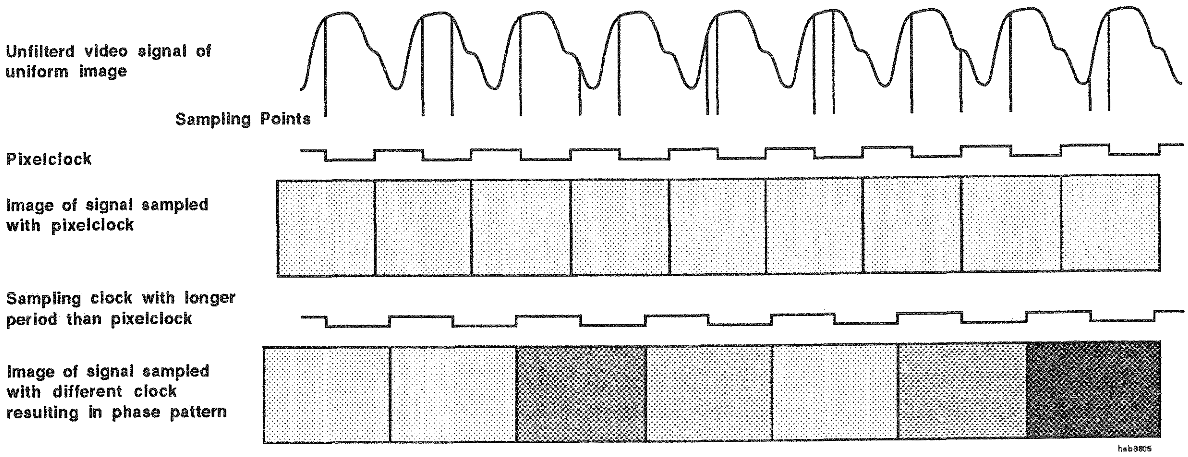

Figure 4: Sampling rate and phase patterns of typical video signal (The drawing is schematic and effects are exaggerated)

3.1. Framegrabbing without Pixelclock

When the pixelclock cannot be used the receiver must either reconstruct the pixelclock assuming a certain number of pixel periods per line (resulting in a variable internal pixelclock frequency), or use a fixed pixelclock period.

3.1.1. Framegrabbing with Variable Pixelclock

Framegrabbers receiving composite video must separate the synchronisation information from the video signal. This is performed by a sync separator, which generates a composite sync signal from the composite video by removing all pictorial information (see Figure 5). A PLL (Phase Lock Loop) tries to match the hsync signal from the camera with an internal hsync signal by varying the pixelclock frequency of the framegrabber, which in turn is used to create the internal hsync. The composite sync can either be directly routed to the PLL or passed through csync-conditioning circuitry. The vsync is detected in vsync detection circuitry (with reference to the frame grabber hsync).

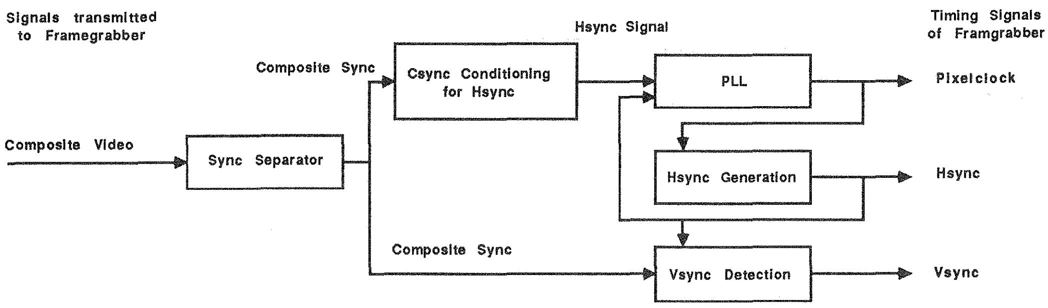

Figure 5: Synchronisation with composite video and PLL

If composite sync is directly passed to the PLL, it is usually gated off during at least the time of equalisation and broadcast pulses, possibly during most of vertical blanking. This is done in order to prevent the PLL from being disrupted by equalisation and broadcast pulses or other "dirty syncs" that might occur during vertical blanking. The PLL is running free during this time. When csync-conditioning is used, composite sync is converted to an hsync signal by removing equalisation and broadcast pulses. The amount of jitter introduced by sync separator and csync-conditioning circuitry is not specified by manufacturers.

When vsync and hsync signals transmitted by a camera are used for synchronisation, these uncertainties as well as problems with equalisation and broadcast pulses do not occur. These signals are continuous, less influenced by other effects and require less electronic elements for their detection. Synchronisation with separate vsync and hsync can be more precise than with composite sync and composite video.
The PLL compares the hsync with its internal hsync (subsequently called fg-hsync for framegrabber hsync), which is derived by the fg-hsync of the previous line and the number of pixels per line, and changes its frequency to decrease the difference between hsync and fg-hsync. The detection of hsync and fg-hsync by the PLL and other elements earlier in the signal path are usually level sensitive and influenced by any changes in the signal level. Linejitter is partly due to changes and/or errors in level detection and phase differences of hsync and fg-hsync. The first can result in big jitters (that are systematically repetitive) such as the ones from peaks in the power supply shown in *Beyer (1987)*, but can also exhibit long periodic influences as shown in *Lenz (1988)*. Linejitter from phase differences of hsync and fg-hsync exhibits periods corresponding to the low pass filter of the PLL, as can be seen in *Luhmann (1987)* and *Lenz (1988)*.
The part of linejitter introduced by the PLL changes according to the characteristics of the PLL's low pass filter, creating a continually changing scale. The amount of PLL induced linejitter in a particular row over time depends on the use of csync conditioning for hsync. With csync conditioning, the hsyncs are continuous and jitter from phase differences should decrease to a level determined by the quality of the PLL, plus jitter due to disturbances from sync separation, csync-conditioning imperfections and level changes. Jitter will oscillate since the PLL will always deviate from the pixelclock rate required (except if the required rate corresponds to the free running frequency of the PLL's voltage controlled oscillator). The chance that the period of these undulations will match the number of lines per field is almost nil, thus the PLL induced linejitter of a particular row will usually change in time. When sync signals are gated off in between fields, the PLL will also drift away from the required frequency and must lock on again for each field. However, this will not result in stable hsync offsets for a particular row of the image over time. If the signal is not gated off, the PLL can be disturbed by the equalisation and broadcast pulses leading to unpredictable disturbances.
The stability in time of a particular system needs to be investigated with respect to precision requirements. An important aspect is the fact that video is generally interlaced, meaning that consecutive lines for the PLL are alternate lines in the image. When specifications for PLLs are given, the performance over the entire frame is relevant for the image row to row linejitter of interlaced images.

3.1.2. Framegrabbing with Fixed Clock

The framegrabber uses an internal fixed clock, usually with a much higher frequency than the sampling clock (pixelclock of the framegrabber) derived from it. An hsync (either the hsync coming from the camera or an internal hsync generated by a PLL) is detected and the divider generating the sampling clock is reset. The same level sensitive effects and instabilities due to sync separation and csync-conditioning for hsync occur. The other effects are quite different though. There is a linejitter component introduced by the timing between the hsync detection and the clock which can be overlaid to undulations from the PLL trying to follow the hsync pulses from the camera.
Linejitter is constant within each row, because the sampling frequency is not changed, providing for a constant scale (assuming that the transmitter has a constant clock). Sampling cannot be adjusted to have the same period as pixelclock, requiring low pass filtering before A/D conversion or digital filtering of the image to remove phase patterns. Without hsync PLL, linejitter in a row is the jitter of the preceding row plus the hsync period, modulo the master clock period. When the hsync PLL is used, it's oscillations are overlayed with the clock reset characteristics. Linejitter of framegrabbers with a fixed clock can reach at least 0.1 pixel, since the fastest clock such a system will have is in the order of 100 MHz, as compared to a typical pixel frequency of about 10 MHz.

3.2. Framegrabbing with Pixelclock

When composite video (or video plus hsync and vsync signals) and pixelclock are transmitted, the frequencies of camera and framegrabber can be locked. A stable phase difference between video and pixelclock must be compensated for by delay elements in the framegrabber. Figure 6 shows the electronic elements and signals involved.

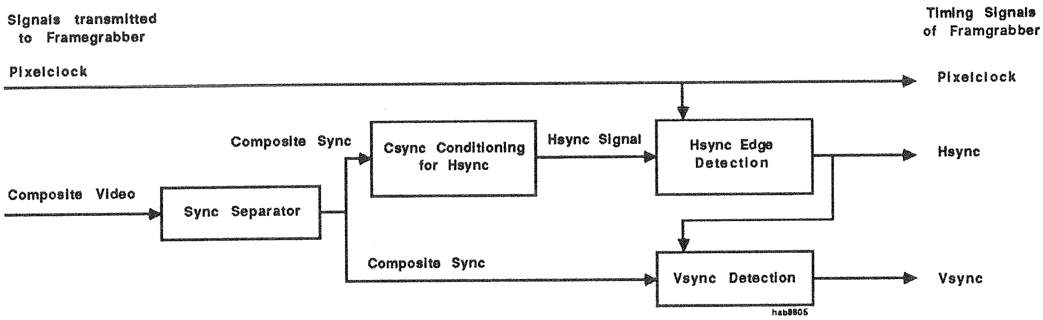

Figure 6: Synchronisation with composite video and pixelclock

The detection of hsync can now be done by an edge detector with reference to pixel clock, eliminating any subpixel linejitter. The most critical part is pixelclock detection by the A/D converter and the timing precision of the conversion with respect to it (these errors do also occur in the systems considered previously). The issue to be evaluated is the relation between the precision of the transmitted pixelclock, the detection and sampling time offset uncertainty, the time required for sampling and/or A/D conversion as compared to the time period for optimum sampling given by the characteristics of the video signal (see Figure on right). The specifications of a typical flash A/D converter indicate a "sampling time offset" of 15 nsec from sampling clock to conversion, with a short-term uncertainty of less than 0.1 nsec. The delay varies from chip to chip and depending on temperature by a few nsec.

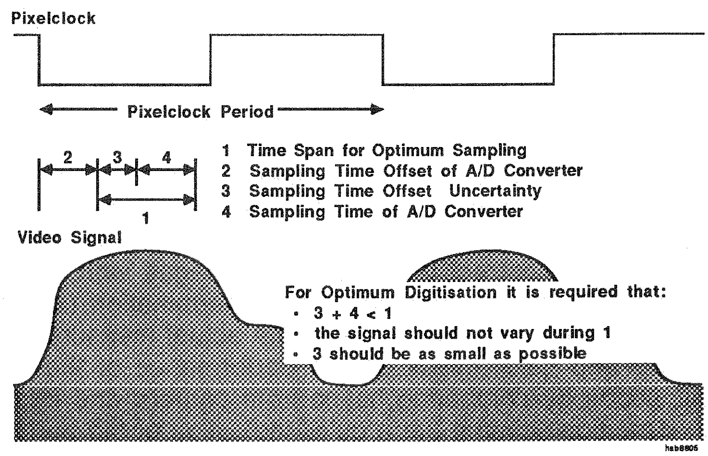

Figure 7: A/D converter timing and video signal

With camera and framegrabber timing locked together by the pixelclock, the scale between sensor and memory image is fixed and the pixel spacing of the digital image corresponds to the sensor element spacing. Changes in the clockrate of the camera, for example due to changes in temperature, have no effect on the signal transmission (assuming that the camera observes rules outlined in the next chapter). Furthermore some synchronisation problems incurred by cameras can also be eliminated with pixelsynchronous framegrabbing.

3.3. Some Camera Requirements

All aspects of synchronisation pertaining to framegrabbers are also applicable to cameras. A few conditions for cameras are:

- When the pixelclock is not transmitted, the camera clock must be absolutely stable.
- All synchronisation signals, and especially hsync, must occur at integral multiples of the pixelclock period.
- The active video time of a line must be an integral number of pixelclock periods and must start at a fixed number of pixelclock periods after hsync.
- All lines of the sensor should be transmitted.

Many cameras do not meet any of these requirements. It is a well known fact that oscillators used in cameras are temperature dependent, leading to so called "warm up effects". Often not all sensor pixels of a line are transferred because the active video time is too short to transfer them with the given pixelclock rate. Some cameras have independently derived timing for sensor readout and synchronisation pulse generation, creating strange offsets between hsync to hsync and hsync to start of active data as well as varying number of pixels per line.
When a camera meets the second and third criteria and transmits composite video (or video plus composite sync or hsync and vsync) and pixelclock, the transmission (digitisation) is immune to changes in the frequency of the pixelclock with an appropriate framegrabber. Such a camera/framegrabber combination can also eliminate synchronisation errors that usually occur when the camera must lock-on to external synchronisation signals.
Cameras accepting an external clock could provide for variability of frame rate. Features such as frame reset, shutters, etc., will be of more interest in industrial environments and dynamic applications with increased requirements on synchronisation and image capture timing precision.

4. Methods for Detection and Compensation of Linejitter

The following will give an overview of methods for the detection of linejitter as well as compensation methods depending on the type of synchronisation mechanism used. Such methods are required to achieve a precision of 0.01 of pixel period in order to match the potential geometric uniformity of current sensor technology. In view of the large magnitude of linejitter (0.4 pixel and more, peak to peak) considerable improvement may be obtained even with lower precision of determination and compensation.
Except for cases where linejitter can be shown to be constant over time, it is necessary to determine and correct it in the same images with which the measurments are performed. This requires that the procedure for determination (and compensation) be performed on the spot, is fast and not obstructive to the actual measurement task.
An easy and quick check on the performance of the hsync detection can be done with an oscilloscope by comparing hsync from camera and framegrabber. This cannot be used for any correction scheme but a quick indication of the performance can be obtained.
Several methods are based on the use of the straightness of lines imaged on the sensor. These methods can achieve a high precision for the location of lines if they have good contrast, a sufficient line width and advanced location algorithms are employed.
Placing a precise grid in front of the sensor provides for a reference that is free of lens distortion. CCD-sensors do have a protective plate in front of them, thus the grid can only be placed at a distance of about 0.5 to 1 mm from the sensor surface, creating considerable problems of imaging the grid with good contrast. The grid might also obscure objects.
Another method is to project a line or lines onto the sensor using a laser and cylindrical lens. The precision of such lines would have to be verified for such systems. This method would be useful for laboratory purposes, and may provide lines with very good contrast that can be located precisely.
Luhmann and Wester-Ebbinghaus (1987) use a glass plate with precise lines in front of the camera and an almost distortion free lens system. This method can also only be used in the laboratory, but has the advantage, as compared to the next method, that effects of lens distortion need not be removed before analysis of linejitter.

Beyer (1987) uses a method based on analytical plumb line calibration. Several lines can be placed at convenient locations in object space. Precisions achieved for the detection are in the order of 0.02 of pixel spacing. The disadvantage of this method is that effects of distortion must be removed before linejitter can be determined. All methods using lines cannot detect linear or long periodic drifts.
Lenz (1988) uses a method that is based on the use of the peaks of pixelclock period usually existing on the video signal. He also adapted cameras such that the pixelclock is purposely added to the video signal making it applicable to images acquired for the actual measurement task. The phase pattern must be removed with appropriate digital filtering. The method has two major drawbacks. First it assumes that the difference between pixelclock periods per line of camera and framegrabber is rather large (in the publications it is at least 20 periods). If a difference of only a few pixel periods would occur, the precision of the method might decrease significantly. Second, only the average jitter over a whole row is determined (although it could be split up into several areas, it could never achieve a measurement at a specified location as small as with methods using lines). Its advantage is that linear and longperiodic drifts can be detected. No clear indication of precision is given, but it is stated that jitter "seems to be long- and short-term stable within 1/20 Pel" *(Lenz 1988)*.

Some methods for the compensation of linejitter were outlined in *Luhmann (1987)* and *Beyer (1987)*, but lacked the reference to the type of synchronisation involved in framegrabbing. The following methods are adapted to the specific synchronisation method used. Correction values of linejitter in systems with variable pixelclock can be interpolated linearly with sufficient precision from two positions in each row (assuming linejitter smaller than 0.4 pixel, peak to peak), even though the change of linejitter is not linear. For systems with a fixed clock it should be sufficient to determine jitter in one position and use this value to correct the row. Naturally more lines should lead to an improvement of the compensation. Procedures for detection and compensation of linejitter require additional steps in the calibration and/or measurement task. The image can either be resampled or the coordinates of a feature of interest corrected. If the image (or at least the regions of interest) must be resampled, the correction procedure is computationally intensive, whereas it is very efficient when correction terms for the image coordinates of features of interest can be determined. Whether or not it is possible to predict the exact influence of linejitter on the image coordinates of other features depending on a particular location method requires further investigations.

5. Current Developments

The performance and capabilities of systems for synchronisation and image transmission are to a large extend determined by the signals employed, thus the following groups are to be considered:

1. Systems with composite video (or video and composite sync)
2. Systems with video and vertical and horizontal sync
3. Systems with any of 1 and 2 plus the use of pixelclock
4. Digital systems

Transmission and synchronisation with composite video is a widely used standard for cameras and framegrabbers. Most framegrabber boards appearing on the market still rely on it, and will continue to do so due to the large base of video products and the increasing use in publishing, advertising and computer graphics applications. On the other hand, these areas, together with broadcasting, are driving the use of HDTV (High Definition TeleVision) which will lead to sensors with better resolution, but not necessarily to better transmission and synchronisation methods.
The use of video with separate hsync and vsync signals is quite rare, but is used in many advanced systems that require higher precision. It represents a significant step since the sensor size is no more limited. Assumptions on the numbers of pixel per line and/or the pixelclock frequency are nevertheless required.

Cameras which also transmit the pixelclock are available on the market and should continue to appear quickly, since it is simple to adapt current cameras appropriately. Cameras meeting the conditions outlined will not be readily available soon, because this requires a considerable redesign of electronics.
Advanced framegrabbers which have inputs for video, hsync, vsync and pixelclock, fast A/D converters (> 10 MHz) and sufficient flexibility to provide for different sensor sizes, impedances, signal types, synchronisation capabilities for cameras, etc. are rare. Currently about five line scan interfaces and framegrabbers with pixelclock input are available. Some are built for specific cameras only; most have too low conversion rates for larger sensors transmitting at video rates (larger than 512 x 512 pixel with at least 25 frames/sec), with only a few accepting frequencies up to 20MHz. For most manufacturers such framegrabbers represent the next generation, currently under development and probably not appearing before 1989.
Digital cameras, which perform A/D conversion on the camera and transmit digital data, are still very expensive and their general availability is limited by the lack of communication standards for interfacing them to (digital) framegrabbers and the high data rates required. Appropriate framegrabbers, or other interfaces with sufficient data rates, are as rare as framegrabbers with pixelclock.
The Megaplus Camera from Videk can be regarded as a typical example of what is to be expected. Besides providing non-composite video (video without synchronization signals) with separate synchronization signals and pixelclock, it also has an 8bit A/D converter and transmits digital data. This indicates that developments are leading away from the use of composite video standards and towards better transmission techniques.

6. Conclusions

Some of the key aspects of CCD-camera calibration, the synchronisation of systems and the transmission of images from sensor to memory, have been investigated. The signals involved and several synchronisation techniques used in framegrabbers have been analysed with respect to radiometric and geometric precision.
Methods for the determination and compensation of linejitter are proposed. These provide for improvements with low-cost systems, still video cameras and other devices with intermediate analog storage, where the pixelclock cannot be used for framegrabbing.
An electronic solution to synchronisation and transmission is given and some requirements for CCD-cameras and framegrabbers outlined. Such pixelsynchronous systems are leading the way towards digital cameras, where image quality can be improved even further by assuring a transmission free of degradations.
The development of testing and calibration procedures requires considerable effort on the part of sensor specialists, electrical engineers and photogrammetrists. The solution of synchronisation and transmission problems, although only one aspect of CCD-camera calibration, will open the way for a considerable improvement of the precision attainable with CCD-camera based systems.

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