PROGRESSIVE-SCAN DIGITAL TELEVISION CAMERA FOR THE PARTICLE BEAM MONITORING

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Abstract

New version of CCD-based digital television camera with embedded Fast Ethernet (100base-T) interface was developed. This camera was designed as a part of the beam parameters measurement system of VEPP-4M and VEPP-2000 electron-positron colliders.

Real-time data transfer via Ethernet network and possibility of connection of two external CCDs are the feature of this camera.

INTRODUCTION

Budker Institute of Nuclear Physics (BINP) is building a few installations (VEPP-2000, FEL) and upgrading an existing collider (VEPP-4). Wide usage of optical measurements is planned in control systems of mentioned installations.

The goal of this work was improvement of previous designed CCD-based digital camera [1] with embedded Fast Ethernet (100base-T), opportune for real-time image processing.

TECHNICAL REQUIREMENTS

In particular, on electron-positron accelerating rings the processing of image created by an optical component of synchrotron radiation (SR) allows one to obtain a number of electron (positron) beam parameters – such as vertical and radial sizes, inclination of axis, position in a vacuum chamber etc. And such diagnostics does not disturb a beam and can work with the extra-low current (down to rotation of single particles) unlike a traditional pickup-diagnostic.

For a number of years on accelerating complexes VEPP-2 and VEPP-4 the CAMAC systems of registration based on the linear CCD (charge coupled device) were used for measuring a vertical dimension of beam. But this system had a series of essential disadvantages (for example, the necessity of pointing on CCD and broadening of an optical image in a transverse direction).

Apparently, the systems based on two-dimensional imagers are free of similar disadvantages. However, practically accessible devices (such as the usual television cameras in combination with videograbbers or the inexpensive digital television cameras) are only restrictedly suitable for beam diagnostics.

For "TV cameras + videograbber" systems the limitations are stipulated by essential non-linearity (from a gamma-correction) and an absence of pixel-to-pixel binding at digitization of the image.

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For rather inexpensive digital television cameras (Web-cameras etc.) a limitation cause impossibility of a considerable diversity of the cameras and computer (for accelerating-storage rings the relevant distances constitute 100m and more) and often because a poor speed.

So a specialized digital television camera on the basis of Sony CCD matrix ICX084AL type was designed (functionally more completed CMOS imagers are worse than CCD because of poor flexibility of application and low sensitivity).

A number of these cameras were applying successfully for VEPP-4 beam diagnostics for two years. Unfortunately, at the present time ICX084AL was substituted for a new CCD (ICX424AL) by manufacturer and a part of camera components came obsolete.

STRUCTURE OF CAMERA

For simplification in tuning and simplification in further modernization the two separate printed-circuit boards are used for analog and digital parts in the new camera. CCD with its drivers and ADC are disposed on the first board, the controller (on the basis of flexible logic), memory chip and Ethernet transceiver are on the second.

ICX424AL (as ICX084AL) is 1/3-inch white & black image sensor with interline organization (when columns of photodiodes alternate with the vertical storage registers, protected from a light). The working area of this device contains 494 columns and 659 rows (i.e. approximately 330 thousands of active square pixels). For obtaining a high sensitivity for such architecture of CCD the matrix of light-collecting microlenses is deposited on the surface, that practically eliminates the "dead" regions of pixels. The saturation charge of a pixel was estimated at 40000 carriers, noise charge - at 20-30 carriers (rms).

Main feature of these CCDs is a progressive scanning. In a combination with effective antiblooming structures providing a controllable "erasing" of photodiode charge (electronic shutter) that allows realize in new camera the regime for registration of momentary images without loss of resolution.

As a previous version a new CCD camera uses Fast Ethernet (100 Mbit/s) interface. This interface has allowed the direct transmission of information to the computer in real-time mode (i.e. immediately after occurrence of the pixel signal on a CCD output). The disadvantages of such solution are double (up to 12.5Hz for frames) decrease of maximal rate of image registration and necessity to connect the camera (or set of cameras) through the dedicated Ethernet line with a high reliability of data transmission and also brings some complication of the software.

However, for beam diagnostics systems these disadvantages are essentially “overbalanced" by a lot of novel abilities.

Firstly, the great (or easily grown) RAM volume of modern personal computer allows to use this “real-time camera” for recording of rather long continuous sequence of process frames (up to 2000 frames for a 1.5GB RAM - i.e. up to 150s of recording with a maximal recording rate).

Secondly, often there is no necessity for storage of a complete image, and the required information (for example, for a system of the beam stabilization it is a coordinate of a light sport) can be obtained by data processing in accordance with their reception from the camera.

In third, it allows to record process "to along fact" - i.e. to begin (or to stop) recording in computer memory only at occurrence of given changes in the image. For example, such condition may be used for fixing of beam crash history.

At the same time, due to application of a chip of programmed logic (PLD Altera EP1K30TC) with 4-times increasing of the number of active cells (in comparison with the previous version) it become possible to increase essentially the volume of microcode, and also to set a memory (SRAM) for one image in the new camera.

It is intended to use the built-in memory (after appropriate modernization of microcode) for implementation of simultaneous recording and successive transmissions of the images by several cameras.

PLD configuration is loaded from EPROM chip by microprocessor. So the contents of EPROM may be changed or checked by the computer through RS232 port without dismantling of camera (directly on the installation).

For synchronization with the processes under investigation the camera has optically isolated input and output lines (the input of "external start" and the output of "synchronization signal").

Analog Devices AD9826 chip is used as ADC in the new camera. It is a 16-bit 3-channel analog signal processor for linear CCD of high-quality color scanners. This ADC has smaller noise and larger dynamic range than previously adapted 14-bit version (AD9822).

AD9826 provides a condition of the correlated double sampling (for reduction of noise and drift), and each its input has individual adjustment of gain and baseline (by loading of the relevant internal registers). Due to a high dynamic range of this ADC it is no necessity of the loaded data modification even at considerable change of an image.

The standard configuration of camera uses only one AD9826 input channel coupled with preamplifier of the basic CCD sensor (disposed in the camera). Nevertheless, the presence of two additional input channels allows involving (if necessary) one or two external CCDs (connected to the camera by flat cables up to 40cm length). This opportunity is useful when the image sensor is required to be disposed in minimum volume, or if two imagers should be disposed side by side. Such cameras with external CCDs will be used for observation of electron and positron beams on VEPP-2000 collider.

MAIN PARAMETERS OF CAMERA

Interface	Fast Ethernet (100base-T)
PC-camera distance, m	up to 100
Connected CCD sensors	1, 2 or 3
Scan mode	progressive
Image size (V×H), mm	3.66 × 4.88
Active rows	494
Active columns	659
Pixel size, μm	7.4 × 7.4
Max. qantum efficiency (500nm), %	55*/40**
Max. sensitivity (rms), photons/pixel	50*/100**
Noise charge of pixel (rms), e^-	30*/40**
Saturation charge of pixel, e^-	40 000*,**
CCD reading time, ms	80
Minimal integration time, ms	0.14
Maximal integration time, ms for standard mode for expanded mode (warm CCD)	 80 ~10 000
ADC resolution (bit)	16
Power consumption (watt)	3.5

*estimation for ICX424AL
**estimation for ICX084AL

CAMERA APPLICATIONS

First of all, new camera was designed for monitoring of the particle beam. And now the set of cameras uses successfully (for examples, [2, 3]) for electron and positron beam diagnostics of VEPP-4M; the eight ones are accommodated for such system of B-4 buster; the next eight ones (with 16 external CCDs) will be used on VEPP-2000 collider.

The opportunity of camera operation both with the small (hundreds of microseconds) and long (more than 10s) time of integration makes it possible to obtain the significant (more than 10^7) range of permissible change of image intensity, which ensures the large range of operating currents of the diagnostic systems. The possibility of integration process initiation from the external start makes it possible to use the new cameras for recording of the single processes (bunch reset, bypass, injection, etc.).

The presence of external start makes the developed camera effective in the number of applications, different from the particle beam observation - first of all, for recording of single-pulse images.

In particular, these cameras are successfully used in the system of plasma diagnostics. The possibility of designed of the recording system for investigation of the shock-wave and detonation processes on the beams of synchrotron radiation (SR) also is considered.

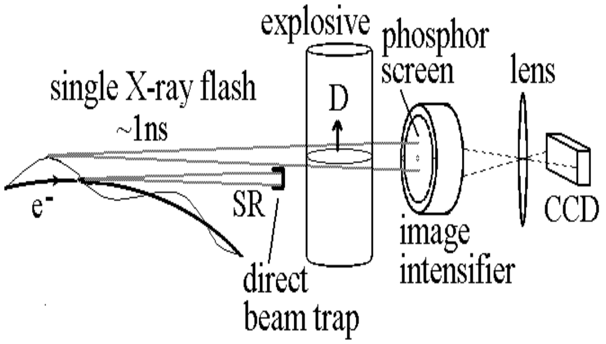

Figure 1: Possible registration scheme of the shadow radiography on a basis of SR single pulse.

In such system (scheme on Fig. 1) the sample under investigation with the shock or detonation wave will be exposed to the short (~1ns) X-ray pulse (a single SR flash of wiggler, formed by the excitation and suppression of the betatron oscillations of electronic bunch [4]). And, at using of heavy (for example, $PbWO_4$) or structured phosphor and image intensifier with the fiber-optic input window, the spatial resolution of obtained two-dimensional "instantaneous photograph" of process can achieve 10-100μm.

In the used variant of camera (detectors for the beam and plasma diagnostic systems) a black-and-white matrix CCDs are used (ICX424AL or an old ICX084AL). However, if it is necessary to create a colour image, it is possible to install ICX424AK sensor (having a built-in mosaic colour filter) without any modification of the camera. For additional, after insignificant alteration of microcode and one printed circuit board the high-resolution progressive-scan CCDs may be used too (black-and-white and colour versions of ICX205 or near infrared ICX285 with 1360 × 1024 pixels).

In particular, it's begun the development of camera modification for Texas Instruments TC237 image sensor. This is a virtual-phase matrix CCD with the frame transfer and with the possibility of progressive scanning. Its special feature is a high speed of the internal frame transfer (12.5MHz shift frequency).

For the special clocking modes the fast accumulation of restricted series of the one-dimensional or small two-dimensional images [5, 6] may be doing in this CCD. In this case the recorded image is projected to the part (one or several rows) of sensitive section (Fig. 2). With the aid of the matched shifts of sensitive and storage sections, the latter is rapidly filled up with the array of images. Then, after filling of the storage section, it is reading by a usual way through the row (output) shift register, and the sensitive section changes in a mode of clearing.

With the size of the working part of storage section of 658 pixels × 500 rows, TC237 can record (with the speed of $0.8 \cdot 10^6$ images/s for VEPP-4) from 33 two-dimensional images (15 lines on 658 pixels in each) up to 500 one-dimensional.

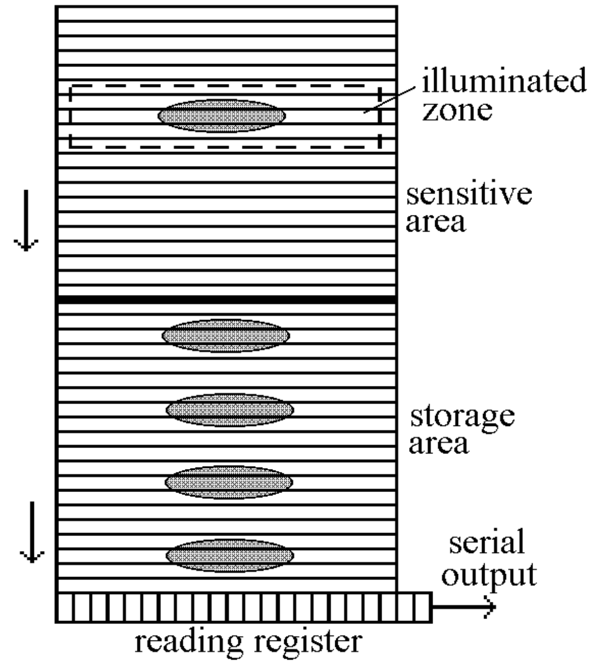

Figure 2: The accumulation of restricted series of images in a frame-transfer CCD.

CONCLUSION

New modification of spatial CCD-based digital camera was designed for particle-beam diagnostics. This camera uses real-time data transmission to computer and so allows decreasing of a feedback delay.

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