CCD detectors for wide field optical astronomy

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Abstract— Modern research trends in optical astronomy, like the "*Pi of the Sky" experiment,* focus on the study of short optical transients. This approach requires completely different construction of the detectors. They must cover large areas of the sky, require high sensitivity and ability to operate automatically. This paper describes the requirements and construction of such detectors for wide field astronomy.

In recent years astronomy evolved towards observations of dynamic objects varying in short (from the human point of view) time scales. Optical counterparts of gamma ray bursts (GRB) are a good example of such phenomena. These events occur a few times a day and are positioned in an isotropic way all over the sky. This implies simultaneous observation of large areas of the sky. The time period of gamma emission varies between milliseconds and minutes, hence it is important to observe optical counterparts with a detector having time resolution of the order of single seconds [1][3].

The requirements for high optical and time resolution of detectors implies the usage of Charge Coupled Devices (CCD). Popular resolution now used in ultra-low-noise cameras is 2048*2048 pixels. Such a number of active pixels generates a large number of data which cannot be simply stored and then processed by the system operators. The classical data processing methodology, used routinely in high energy physics, was applied to reduce the number of finally stored results. The project under description consists of 32 cameras, containing 2048×2048 pixels each, working in parallel, and covering a large part of the sky. The lenses with a focal length of 85 mm give about 0.6 arc min of the resolution [2].

Requirements for hi-grade astronomical CCD cameras

There are many models of astronomical CCD cameras produced and available on the market. But they have several disadvantages that seriously limit their usage in astronomical applications. The main reason is not sufficient reliability of the internal mechanical shutter which usually does not exceed 100.000 cycles, while the required number is ~10^7. They are rarely equipped with features like: lens heating, temperature and humidity sensors, remote adjustment of lens focus. The ADC resolution usually does not exceed 12bits at 1MHz or higher readout frequency. These factors forced us to develop custom CCD detectors, better suited to the requirements of the project [4][6].

The requirements for the detector are the following:

- Remote adjustment of all critical parameters,
- Autonomous operations,
- Self diagnostics,
- Immunity to climate conditions like humidity and temperature changes,
- Remote firmware upgrade,
- Open communication protocol,
- High sensitivity, limiting magnitude about 11-12 at 10s of exposure time,
- Low readout noise, below $20e^-$,
- Dead time < 2s,
- Shutter endurance > $5*10^6$ which ensures continuous operation for 10 years at shutter time of 5s,
- High speed interface capable of transferring 1 full picture (8MB) in less than 1s,
- Humidity and temperature sensors.

Fig. 1. Assembled K20/30 CCD camera without a cover

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K20 and K30 astronomical cameras

There were developed several detector versions. Currently, there are used K20 [4] and K30 [6] camera models. They share the same package and analogue front-end (Fig. 1). The difference is in the communication and control blocks.

The features of the K20 and K30 detectors are the following:

- Remote control of all the critical functions: readout frequency, gain, CCD temperature, mechanical shutter, lens position.
- Remote monitoring of atmospheric conditions. The temperature and humidity are measured inside the CCD sensor chamber and outside the device. The humidity of the CCD circuit is a relevant factor, because the sensor works at a very low temperature, which may cause water condensation. The presence of water can damage the costly sensor.
- Possibility of remote firmware upgrade (micro PC program and FPGA configuration).
- Watchdog Timer which protects electronics against unwanted work conditions.
- Embedded Linux operating system (K30).

The electrical specifications of the K20 and K30 CCD camera models are the following:

- STA0820A CCD sensor, resolution 2048×2048 pixels, 15×15µm each,
- Dual channel readout,
- Readout time : from 1s till 1min,
- Noise: < $16e^-$ at 2 MHz readout frequency, < $12e^-$ at 1MHz,
- ADC: 16bit, CDS readout technique,
- Interfaces: USB2.0 HS, max transfer speed: 52MB/s, Gigabit Ethernet UDP protocol, 100MB/s max, (Ethernet 100Mbit, TCP/IP for K30),

The mechanical specifications of the K20 and K30 CCD camera models are the following:

- Active thermo electrical cooling, 40° below ambient temperature, equipped with a local heat sink and a mechanical fan,
- Optional lens heating which prevents water condensation,
- High durability (>10^7 cycles) mechanical shutter,
- Lens focus remote control,
- Separate CCD sensor chamber filled with a noble gas to prevent recontamination,
- Immunity to the weather conditions present at the observatory site.

Hardware description of K20 and K30 CCD cameras

The detector electronics is based on the current FPGA circuit technology (Fig. 2). This approach enables comparatively easy and seamless modification of the device functionality and significantly reduces components count. In the camera prototypes there were used Altera Cyclone VLSI circuits, with Active Serial configuration scheme, which resulted in further simplification of the electronic system.

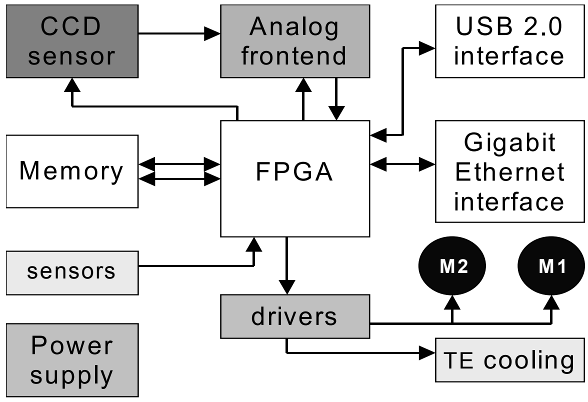

Fig. 2. Block schematics of Camera electronics

The FPGA implements SDRAM memory controller, CCD and ADC readout state machines, USB and Ethernet controllers, and sensors readout blocks. Detector control functions are performed by the FX2 microprocessor built into the USB interface. It is an enhanced version of a popular 8051 microprocessor. The microprocessor takes responsibility for the following functions:

- Interpretation of commands from a host PC,
- Shutter and focusing motor control,
- Setting up transfer, video processor, exposition and readout parameters,
- FPGA configuration update - Active Serial FLASH programmer,
- Readout of temperature sensors,
- Ethernet interface PCI master/slave state machine control,
- ARP, IP, UDP, ICMP, NUDP protocol stack implementation.

In the case of a K30 detector, the role of an FX2 processor and a gigabit Ethernet interface is performed by ARM9 processor.

A block diagram of the digital signal path in the ultrasensitive CCD camera system is presented in Fig. 3. The 8 bit data from the video processor is fed into the FPGA circuit and then recovered to its original 16bit form. Next, the data is transferred into the memory. One full picture takes over 8MB of data. The data are stored there waiting for the USB or Ethernet transfer request. When such a request occurs, the data are read from the SDRAM and transferred into the USB/ETH interface. Here, the data are divided into 512B packets for USB (1024B for Ethernet) and sent to the host.

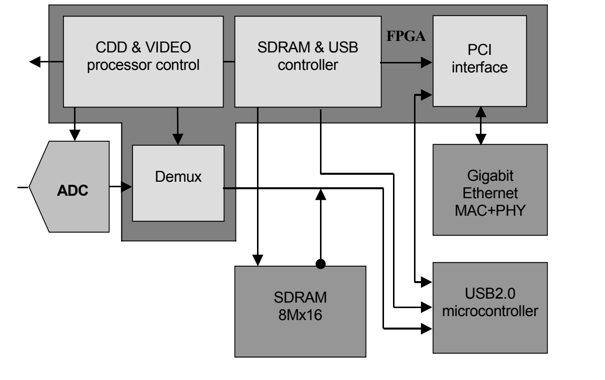

Fig. 3. Schematics of digital processing circuit

A block diagram of the analog signal path in the ultrasensitive CCD camera system is shown in Fig. 4.

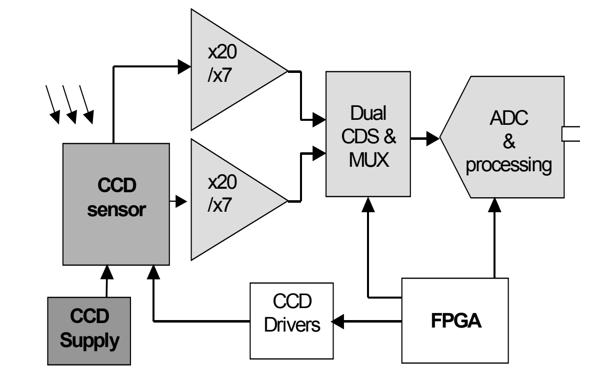

Fig. 4. Schematics of analogue processing circuit

The signal generated during the CCD readout is initially processed by a preamplifier. It performs the following operations:

- Signal DC restoration,
- Amplification (switchable),
- Reset pulse suppression.

Its construction is based on a fast operational amplifier with JFET inputs.

The next stage of signal processing is done by a video signal processor. It consists of 16bit 15MS/s ADC and a triple analog signal processing path. The functions to be performed are as follows:

- DC restoration,
- Programmable DC subtraction,
- Amplification (factor 1-6 controllable in 64 steps),
- Correlated Double Sampling,
- Analog to digital conversion,
- Digital bus multiplexing (to reduce number of wires).

Output data are then processed by the logic circuits in the FPGA. In the same circuits the signals are generated that control charge transfer in the CCD sensor. After the signal level conversion, they are fed into the drivers. The drivers are directly connected to the CCD electrodes.

Application and further development of K20 and K30 cameras in the Pi-of-the Sky experiment

The parameters of the described cameras are satisfactory for 10s exposure time used in the "Pi of the Sky" experiment. There is also prepared a version of the experiment which will significantly shorten the exposure time and eliminate the detector and measuring system dead time to several μs. The optical range of the system needs to be preserved. This means the required improvement of the signal to noise ratio by a factor of 10. There are several ways to achieve this requirement.

A new family of Electron Multiplying CCDs (EMCCD) enable operation with readout noise < 1e$^-$. Using the EMCCD circuits, in new cameras, may help to keep the noise low, but the multiplication of electrons is a stochastic process which inherently generates noise. This noise may seriously perturb the photometry. Moreover, the available EMCCDs maximum resolution is only 1024*1024pixels. They work in a frame transfer mode, thus eliminating the need for an external, reliable shutter and minimizing the dead time to several μs.

An alternative method is the usage of standard CCDs, working in a frame transfer mode. This eliminates dead time and the need for an external shutter. But the shutter is anyway needed for dark frame acquisition. The required increase of SNR by a factor of ten can be obtained using the pixel binning technique and the usage of a back thinned CCD with a higher quantum efficiency.

Thanks to the progress in ADCs construction, it is possible to obtain much lower readout noise using oversampling techniques and implementation of the Correlated Double Sampling in the digital signal domain.

The next generation of intelligent and remotely controlled detectors for demanding astronomical applications are currently under development.

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