Cooling CCD camera based on embedded system

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Abstract: A new kind of cooling CCD camera based on an embedded system was designed according to the characteristics of the astronomical camera. Using Cortex-M3 ARM as the hardware design platform, the cooling CCD camera performed excellently in the astronomical observation. CCD vertical clock driver was designed with a CXD1267 chip, and the analog signal was correlated double sampled by an AD9826 chip. The ARM chip was used for the design of CCD driver timing. Because of the timer interrupt of the microprocessor, the temperature of the CCD chip was controlled in real-time by a Peltier cooler module. Three primary kinds of noise in the presented camera system were analyzed. The influences of the working temperature and exposure time on the noise were studied in experiments. Several measures to reduce the noise of the CCD camera were discussed.

Key words: embedded system; astronomical CCD camera; Peltier cooler; noise

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嵌入式系统的制冷 CCD 相机

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摘 要： 根据天文摄影中 CCD 的工作特性，提出了基于嵌入式技术制冷 CCD 相机的新方法，以 ARM 微处理器为硬件平台设计了嵌入式制冷 CCD 相机，并在低照度下的天文观测中取得了良好的效果。基于天文制冷 CCD 的具体特性和对信号数据输出的要求，选用 CXD1267 和 AD9826 分别设计 CCD 的列转移驱动时序和 CCD 的水平读出时序。通过微处理器定时中断，实现对 CCD 制冷温度的实时控制。分析了科学级 CCD 噪声的种类及来源，通过实验得到了温度、曝光时间与暗电流噪声的关系以及 CCD 的读出速率与读出噪声的关系。进而在硬件和软件上采取了相应的措施有效地降低了 CCD 的噪声。

关键词： 嵌入式系统； 科学级 CCD； 珀尔帖制冷器； 噪声

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0 Introduction

To obtain dark deep space astronomical pictures, a camera which can perform excellently during long exposure time in low light condition is required in the astrophotography. Compared with the CMOS image sensor, CCD image sensor with the advantages of lower readout noise, higher sensitivity, larger dynamic range and unlimited exposure time has been widely applied in astronomical field.

Among all the problems in applications of CCD, the most important one is CCD driving method. The generation of an image is composed of four steps: integral — shifting — transfer — output. Considering the diversity and complexity of CCD drive timing, a series of voltage levels are needed to drive CCD [1]. Meanwhile, an excellent driving method also has positive influence on signal processing, conversion efficiency, SNR and other features of photoelectric conversion. Thus, the key of designing a CCD camera used in low - light environment is to design an excellent diving method so that the CCD sensor can work in the best condition.

Traditional CCD camera works with high driving frequency and needs high readout speed to deal with its massive complex data, thus arousing the high demand for High - speed data collecting system. The implementation of traditional driving method is generally based on CPLD or FPGA[2]. Considering that the astronomical cooling CCD is a kind of slow scanning camera mainly used to observe weak luminescence stars in deep - space during night, a CCD camera based on an embedded system can meet the requirements of the diving frequency [3]. Furthermore, its advantages of flexible adjustment of time driving, easy programing, micromation, and low power consumption also makes it stand out. Therefore, a cooling CCD camera based on the embedded system is presented here.

1 Hardware system design

Based on ICX285AL CCD image sensor, the astronomical camera was designed with the merit of high resolution, low noise, and adjustable exposure time, the temperature of the CCD sensor was real - timely controlled through a Peltier Cooler in any given exposure time.

The hardware structure schema of the cooling CCD camera is shown in Fig.1. It mainly consists of a power supply module, a CCD sensor, an A/D converter module, a Peltier (TEC) module [4], a USB interface module and an embedded system module. Due to the restrictions of installing space, the digital circuits of CCD camera should be placed near the CCD chip from which analog is exported, which also helps further reduce the noise of readout circuit, increase low light sensitivity and dynamic range.

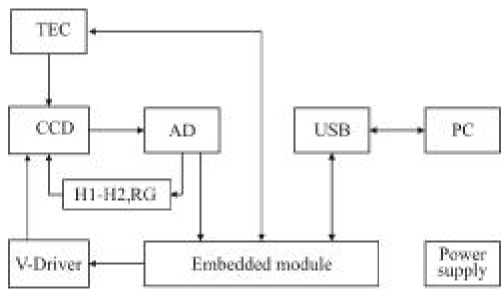

Fig.1 Schematic overview of the cooling CCD

1.1 CCD driving method

The embedded system was based on Interline - transfer CCDs. There are two readout modes of CCD: progressive scan mode, in which all pixel signals are readout in non - interlace format in 1/15 s; high frame rate readout mode, in which all effective areas are scanned in approximately 1/60 s by reading out two out of eight lines (1st and 4th lines, 9th and 12th lines, and so on). The high frame rate readout mode emphasizes processing speed over vertical resolution and is four times as fast as the progressive scan mode. In the astronomy applications, accuracy is more important than readout rate, so the readout rate can be kept in a relatively low level and the CCD was designed to work in the progressive scan mode. The driving signals included five timing signals, and four power supply voltages are needed, which include +12 V, +5 V, -7 V, +3.3 V. The drive timing chart (vertical sync) is shown in Fig.2.

Since the MCU is based on an embedded system, the output voltage of its I/O interface is restricted to +3.3V. So a CXD1267 driver chip was needed to provide the appropriate voltage i.e. -7V to make sure that the CCD can work in the normal condition[5].

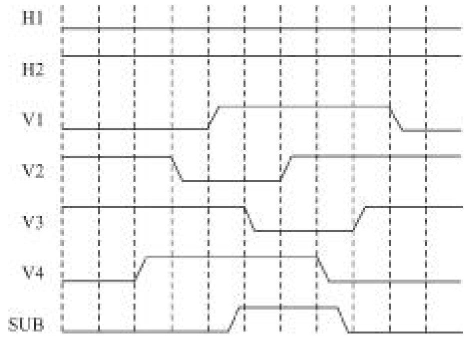

Fig.2 Drive timing chart (column jump)

1.2 Signal transmission and collection

The main content of signals transfer and acquisition is the front-end processing of the horizontal shift register and the A/D conversion. Though a large amount of data was generated during the long exposure time, considering the transfer rate can be set at a low level, a 16bit A/D conversion chip AD9826 is able to satisfy the need. The speed of the A/D conversion can be up to 12.5 MSPS[6]. 1-Channel CDS technology had been used to reduce the dark current noise and other inherent noises at the appropriate sampling time in the front-end signal processing; signal voltage clamp technology had been used to make the output signal voltage match with the A/D input range. The 1-Channel CDS mode timing chart is shown in Fig.3.

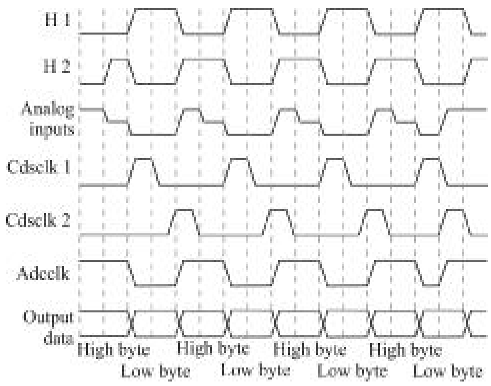

Fig.3 1-Channel CDS mod timing

1.3 Power supply

The system was powered by +12V power source. Since a series of voltages are needed to drive CCD and TEC, we need to step-up, step-down, reversed the +12V power to provide those voltages. LDO and DC-DC chips were used to design a stable, low power consumption system. In addition, considering the working current that TEC needs, +6.5V power source was chosen to power the TEC. Furthermore, through the PWM settings, the refrigerating efficiency can be controlled by changing the duty cycle of the TEC. Compared with the +5V voltage, TEC works better with +6.5V power source, thus, we chose +6.5V to supply the power in the experiment. The work flow chart of the TEC is shown in Fig.4.

To prevent the TEC from staying in working state or nonworking state all the time during long exposure time, we adopted timer interrupt, based on the characteristics of embedded system, which made TEC's working state changed along with timer interrupt. Specific to this embedded system, the temperature of TEC will be checked every 2 s so that temperature control of CCD can be more precisely, if it is below the target temperature, TEC stops working; to the contrary, TEC starts working.

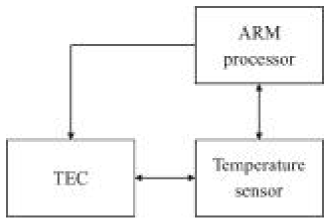

Fig.4 Work flow chart of TEC

1.4 Software development

Homologous software had been developed to make it easier to set CCD exposure time and refrigerating temperature, open and save the images. The software communicated with the embedded system through the USB cable. A FT232HL chip had been taken to communicate with the host computer software conformed to the RS232 protocol. Effective pixels of the CCD is 1 392(H)×1 040(V), the first line of CCD data was taken up by temperature and exposure time instead of signal charge, then they will be transferred to the PC with the rest 1 039 lines. The work flow chart of the software is shown in Fig.5.

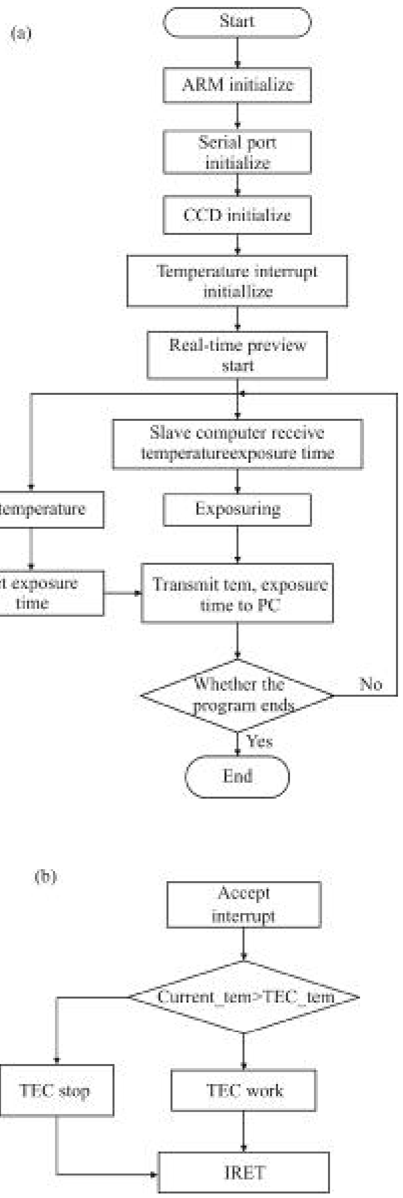

Fig.5 Work flow chart of software

1.5 PCB design

The size of PCB was restricted by the capacity of the telescope where the PCB will be installed. Therefore, the heat dissipation must be the main concern throughout the design. Also, the chips will generate massive heat and noises during working as a result of the complex power systems. Given these facts, the PCB was designed with a radiator and a fan for cooling. In order to make the refrigeration effect better, several improvements on the mechanical shape had been made to enhance the airflow on the PCB surface.

2 Noise analysis

CCD camera noise falls into three categories: shot noise, dark current n oise and readout noise. All these three kinds are related to CCD's working temperature, exposure time and the readout rate of the CCD to some extent.

2.1 Shot noise

Both light and electric current is made of scattered and quantized wave packets in motion. Because of the wave particle dualism, when the light is injected into light sensitive area, the generation of signal charges can be seen as a separate, uniform and continuous random process. The number of signal charges generated per unit time is not absolutely permanent, instead it changes in a tiny range around the average value. When the number of signal charges is too small to cause the statistical fluctuation during the data reading, the statistical fluctuation that been read out is called shot noise.

One of the most important characteristics of shot noise is that it has nothing to do with frequency and it has a uniform power distribution over a wide frequency range. RMS equation is used to describe the relationship between the shot noise intensity and the signal intensity. The equation is shown as below.

$$N_p = \sqrt{S} \qquad (1)$$

In which is shot noise intensity, and is signal intensity.

Longer exposure time not only increase the signal intensity directly, but also increase the shot noise intensity.

2.2 Dark current noise

Dark current is the constant response exhibited by a photosensitive device when no photos are entering the device. It is a relatively small current that flows through the device. The dark current noise is mainly caused by the thermal excitation on the depletion layer. The thermal excitation is a random process which obeys Poisson distribution. Due to the local presence of lattice defects or impurities in the CCD array, there may formed dark current spikes. Since the integrating areas of each signal charge packets and the readout paths are different, the dark current of each pixel are not uniform, thus causing wide fluctuation of background. And this is the reason of the often called fixed image noise.

Because of the existence of dark current noise, SNR of the CCD is affected. In order to eliminate the influence of dark current noise in the image correction, a series of dark field pattern should be read under the same condition which means same temperature and same exposure time, and then these patterns are averaged to get the main dark field pattern.

To reduce dark current noise, astronomical CCD cameras generally worked in low temperature environment[7]. Moreover, the exposure time also have an impact on the dark current noise. In this paper, TEC had been used to cool the CCD, and the dark current noise was reduced effectively. The cooling efficiency was determined by the temperature difference between two ends of the TEC.

2.3 Readout noise

Readout circuit will bring in electrical noise, meanwhile the measuring of the signal will also give rise to some kind of uncertainty in the CCD camera system. All these noises make up the readout noise which represents the error brought in during the process of quantization. In order to enhance the ability of detecting weak luminescence stars in deep space, the readout noise should be reduced[8].

The readout noise consists of two parts: one comes from output amplifier and driving circuit, while the other is related to the readout rate of signal, the basis circuit and the video processing circuit.

As the readout noise was generated while the signals were reading out, it has nothing to do with the integrating time. In this CCD, the readout noise was reduced by slowing down data readout rate and making CCD work in low temperature.

3 Experiments

According to the analysis above, both temperature and exposure time were tested to examine the performance of CCD.

The CCD was tested in complete darkness and the A/D conversion module was set at 16-bit mode. The cooling temperature and exposure time were variable. Specific experimental procedures are as follows:

(1) Set the CCD exposure time as 0 s.

(2) Take 7-25 ℃ as temperature range, images were acquired and then saved every 2 ℃, considering the accuracy of TEC cooling.

(3) Set the CCD exposure time as 1 s, 5 s, 10 s, 20 s, 30 s, 40 s, 50 s, 60 s, then repeat step 2.

(4) Set the CCD cooling temperature as 7 ℃.

(5) Take the exposure time as 0 s, 1 s, 5 s, 10 s, 20 s, 30 s, 40 s, 50 s, 60 s, then acquire and save the corresponding CCD images.

(6) Repeat step 5 every 2 ℃, till the temperature is up to 25 ℃.

4 Analysis of experimental results

The standard deviation shows how much variation or dispersion from the average exists. A high standard deviation indicates that the data points are spread out over a large range of values; a low standard deviation indicates that the data points tend to be very close to the mean. Given the former conclusion, the background fluctuated widely because of the dark current noise. Therefore, we adopted the standard deviation of the gray value of the related image to evaluate the dark current noise[9].

In this paper, MATLAB had been used to read the image, and then get the average gray value of all the pixels. The formula is shown as follow.

$$\bar{x}=\frac{1}{N}\sum_{i=1}^{N}x_i \tag{2}$$

Where $\{x_1, x_2 \ldots x_n\}$ are the observed gray values of all pixels and $\bar{x}$ is the mean value of these observations, while the denominator **N** stands for the quantity of pixels in each image.

The standard deviation of gray value was calculated by the formula shown below:

$$STD=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-\bar{x})^2} \qquad (3)$$

The curves which show the relationship between exposure time and standard deviation are plotted with standard deviation as the ordinate and exposure time and temperature as the abscissa, which are shown in Fig.6 and Fig.7 respectively.

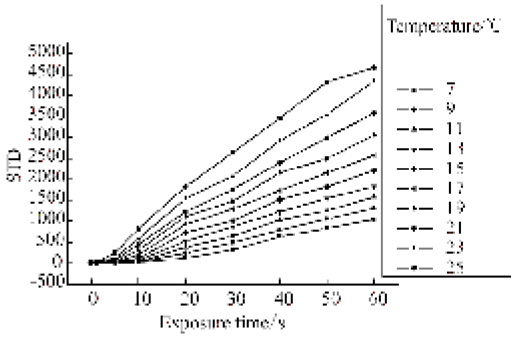

Fig.6 STD versus exposure time

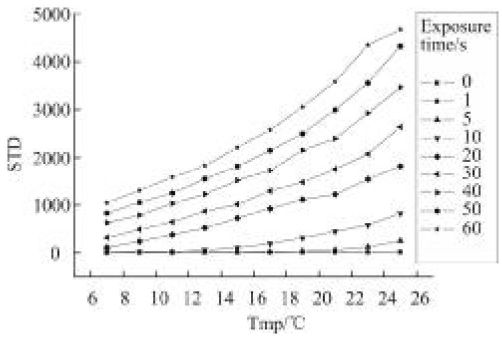

Fig.7 STD versus refrigeration temperature

The curves above show that both exposure time and temperature have a close relationship with the standard deviation, and that the standard deviation will increase while exposure time or temperature increases.

The curves also indicate that temperature plays a more important role in reducing the dark current noise in comparison with exposure time. When the working temperature was set to 7° and exposure time was 0 s, the standard deviation can be as small as 14.248. However, when the exposure time was longer than 5 s, the standard deviation increased prominently. And when the exposure time increased to 60 s, the standard deviation can reach 1 044.5.

While the exposure time is constant, as the temperature increases, the standard deviation's growth will get faster and faster. When the exposure time was 0s, the standard deviation fluctuated around the value of 14.248. The standard deviation had the minimum growth rate when the temperature was 7 ℃.

Experiments show that reducing temperature and exposure time can help reduce the dark current noise effectively.

5 Conclusions

The cooling CCD camera based on the embedded system can meet the basic requirements of astrophotography. With an advantage of flexible adjustment of time driving and easiness for programing, the camera will be easy to be upgraded. As it only occupied a small space and has low consumption of power, CCD camera is convenient to work outside and easy to be taken along with.

From the result of the experiments, several means below can also help reduce the noise further.

Firstly, reducing the working temperature. In this CCD camera, the actual working temperature is set to -25 ℃ below the environment temperature, considering the efficiency of the Peltier Cooler module. So, we can change the mechanical appearance or fix more fans to enhance the heat dissipation.

Secondly, shorter exposure time. The noise will indeed reduce while the exposure time decreases, however, by doing so, the image signal will also reduce along with exposure time. To increase the effective sensitivity, pixel binning is performed in the image editing software we designed.

Thirdly, lower readout rate will also help to reduce the readout noise.

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