Implementation of Astronomical CMOS Camera Test Platform and Control System (Postprint)

Authors: Luo Zhiyuan, Xu Jun, Liu Liming, Zhang Tao

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Abstract

CMOS cameras are important solid-state imaging devices. With the continuous improvement in the performance of scientific-grade CMOS cameras, they are now widely used in scientific research. The imaging equipment of the New Vacuum Solar Telescope (NVST) at Fuxian Lake also uses CMOS cameras. Therefore, establishing an astronomical CMOS camera testing system is of great significance for the acceptance of newly purchased CMOS cameras and the regular inspection and maintenance of existing ones. This paper introduces the hardware composition of the astronomical CMOS camera testing platform, proposes a design scheme based on TCP/IP protocol and serial communication to address the requirements for equipment control in actual testing and the direct control of corresponding equipment using controllers, and designs a multi-threaded parallel control system software using the C# programming language to achieve remote parallel control of various devices within a local area network. Through operational testing of the equipmen

Full Text

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Luo Zhiyuan[1],[2], **Xu Jun**[1], **Liu Liming**[1],[2], **Zhang Tao**[1] [1]Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China [2]University of Chinese Academy of Sciences, Beijing 100049, China

Abstract: CMOS cameras are important solid-state imaging devices. As the performance of scientific-grade CMOS cameras continues to improve, they are now widely used in scientific research. The imaging devices of the New Vacuum Solar Telescope (NVST) are also using CMOS cameras. Therefore, establishing an astronomical CMOS camera test system is of great significance for the acceptance of newly purchased CMOS cameras and for the regular testing and maintenance of existing ones. This paper describes the hardware components of the astronomical CMOS camera test platform. To meet the requirements of equipment control in actual testing, and to enable direct control of the corresponding equipment through a controller, a design scheme based on TCP/IP protocol and serial communication is proposed. A multi-threaded parallel control system software was developed using the C# programming language to realize remote parallel control of each device within the LAN. Through operational testing of the equipment, the results demonstrate that the system can effectively control the normal operation of all devices and meets the requirements for integrated control of the test system.

Keywords: CMOS camera test platform; control system; remote control; EMVA 1288

0 Introduction

The New Vacuum Solar Telescope (NVST) at Fuxian Lake Observatory is currently the largest solar telescope in China and the largest vacuum solar telescope in the world. It is primarily used for high-spatial-resolution imaging observations of the solar photosphere and chromosphere, as well as high-spectral-resolution spectroscopic observations [1]. Photoelectric detectors are indispensable terminals for telescope observations. As a type of photoelectric detector, CMOS image sensors have seen their performance continuously improve with the development of very-large-scale integrated circuit manufacturing technology. CMOS cameras are now widely used in aerospace, biomedicine, astronomical observation, and many other fields due to their advantages of large dynamic range, fast readout speed, low power consumption, and low cost [2].

In the field of astronomical observation, particularly for two-dimensional solar imaging detection, CMOS cameras are extensively used. In recent years, the imaging terminals of NVST at Fuxian Lake Observatory have also adopted CMOS cameras. On one hand, when purchasing CMOS cameras, it is first necessary to understand their performance parameters to determine whether the camera can meet the requirements of the entire observation system. However, in practical applications, the specifications provided by manufacturers are typically based on television broadcast industry standards and often lack the metrics required for actual astronomical observation applications. Even when manufacturers provide performance parameters needed for astronomical observation, these are generally typical values obtained from tests conducted before the chip leaves the factory. Due to variations in manufacturing processes and semiconductor materials, the actual performance parameters of CMOS cameras may differ from the provided typical values, which can introduce errors in methods such as fluctuation correlation spectroscopy or computational imaging [3]. Therefore, before designing an imaging system, it is essential to test the performance parameters of the CMOS cameras to be used.

On the other hand, during camera usage, performance parameters may also change due to component aging and other reasons, thereby introducing additional noise into spectral imaging and causing errors in observational data. This increases the difficulty of analysis and processing and may even lead to incorrect conclusions. Therefore, regular testing and calibration of astronomical cameras are also necessary. In summary, establishing an astronomical CMOS camera test platform is of great significance. This platform can be used for acceptance testing of newly purchased cameras and for regular testing of astronomical CMOS cameras to ensure that their performance meets the requirements of astronomical observations.

1 Overview of the Astronomical CMOS Camera Test Platform

This test platform was established based on the European Machine Vision Association Standard 1288 (EMVA 1288) for image sensor and camera performance testing. For a long time, there was no unified testing standard for CMOS, with almost every manufacturer having their own standard, making it necessary to convert parameters when comparing performance between different cameras. Fortunately, after 2005, with the support of the vast majority of manufacturers —including almost all well-known domestic and foreign manufacturers such as Andor, PI, Hamamatsu, and pco—a unified industry standard was established. The standard clearly defines the camera model, as shown in [Figure 1: see original paper], as well as the parameters to be tested, testing methods, and procedures based on this model [4].

[Figure 1: see original paper] shows the physical model of the camera and the mathematical model of a single pixel. Figure 1(a) describes the physical model of the camera provided by EMVA 1288. A certain number of photons irradiate the pixel, and after a period of exposure, electrons are generated. These electrons are converted into voltage values through capacitor plates, and the voltage values are amplified and converted to digital gray values via analog-to-digital conversion, which constitutes the digital output signal of the CMOS camera. Figure 1(b) describes the mathematical model of a single pixel provided by EMVA 1288, where and σ represent the mean and variance, respectively, and the unknown quantities to be measured are marked in red. Through the internal photoelectric effect, the pixel converts the number of photons into a corresponding number of electrons. This process introduces dark current noise, which is then amplified together by the system gain, after which quantization noise is inevitably introduced during analog-to-digital conversion [5].

This project aims to build a set of test equipment (including hardware and software) that complies with the EMVA 1288 standard and to conduct corresponding parameter tests according to the testing procedures defined in the standard. The test parameters that the current test platform can complete are listed in .

Parameter List

Parameter	Unit/Description
Gain K, 1/K	DN/e^- and e^-/DN
DSNU1288	DN and e^-
Maximum SNR (SNRmax)	Ratio, dB, or bits
SNR^{-1}	Indicates central wavelength, using electrons, photons, or photons/ m^2 as units
PRNU1288	Ratio, dB, or bits
Nonlinearity error LEmin, LEmax	DN and e^-
Absolute sensitivity threshold	Indicates central wavelength, using electrons, photons, or photons/ m^2 as units
Dynamic range (DR)	Ratio, dB, or bits
Doubling temperature (Td)	DN/s and e^-/s

In addition to completing the measurement of the above basic parameters, this test platform is mainly used for studying camera characteristics. For example, research on camera non-uniformity: for astronomical CMOS cameras, non-uniformity is a critical factor that seriously affects imaging quality. Due to the obvious time-varying characteristics of non-uniformity [6], it is difficult to correct through traditional flat-field correction methods. Therefore, we aim to use this test platform to carefully study the time-varying patterns of non-uniformity and thereby find solutions to eliminate it.

2 Construction of the Test Platform

The test platform mainly consists of four parts: the optical field generation section, the darkroom section, the translation stage section, and the environmental monitoring and control section. Its composition block diagram is shown in [Figure 2: see original paper].

The primary function of the optical field generation section is to produce stable, uniform white light and uniform monochromatic light. Uniform white light is used to measure camera sensitivity, linearity, and non-uniformity, while uniform monochromatic light across the entire wavelength range is required to measure quantum efficiency at different spectra. Therefore, the optical field generation section mainly consists of a regulated power supply controller, light source, monochromator, and integrating sphere. The regulated power supply controller provides a stable and adjustable power supply for the light source to prevent measurement errors caused by light source jitter due to current fluctuations. We use Newport’ s OPS-Q250 ultra-stable power supply with a control accuracy of 0.1 A. The stability of the lamp’ s wavelength and output intensity is mainly achieved by maintaining constant temperature and pressure of the halogen gas inside the lamp housing as much as possible. The OPS-Q250 power supply provides highly stable current to the filament, keeping the lamp’ s output intensity fluctuations below 0.05% rms while maximizing the lamp’ s lifetime. The lamp is an Osram 24V-275W quartz tungsten halogen bulb with an emission range covering the entire visible light band. We collimate the light emitted from the source using an aspheric lens (plano-convex lens) with a focal ratio of 2.2 to form a beam with diameter D = 33 mm. The beam is then focused and re-collimated through a convex lens with focal length f = 100 mm and a concave lens with focal length f = 30 mm to form a beam with diameter d = 10 mm that enters the monochromator’ s entrance slit. Its optical path diagram is shown in Figure 3: see original paper. After passing through the mirrors and grating inside the monochromator for spectral separation, the beam exits from the outlet slit, as shown in Figure 3: see original paper, and enters the integrating sphere to form uniform monochromatic light after passing through a filter.

The primary function of the darkroom is to provide a non-illuminated dark field and a relatively stable testing environment for the CMOS camera. The overall dimensions of the darkroom are 1740 × 1000 × 1000 mm, divided into upper and lower sections. The lower section is used to place the dryer and refrigeration unit and serves a supporting function, while the upper section is used to place the translation stage, as shown in [Figure 4: see original paper]. The inner wall of the darkroom consists of a thermal insulation layer and an air circulation layer. The thermal insulation layer uses insulation cotton to ensure that the temperature inside the darkroom does not change significantly with external temperature. Testing shows that when the room temperature is 20°C and the darkroom temperature is 10°C, the time required for natural temperature rise of 1°C is 5 minutes, which can ensure testing of CMOS cameras under constant temperature conditions. The air circulation layer contains a thermoelectric cooler, heater, and fan, which can quickly bring the darkroom temperature and humidity to the required testing conditions and ensure relatively uniform temperature and humidity distribution throughout the darkroom.

The primary function of the translation stage is to provide a fixed position for the test camera and to adjust the relative position between the camera and the integrating sphere’ s exit port. The translation stage mainly consists of a camera mounting platform, lead screw, support pillars, sliding grooves, motor, and motion control module. The maximum travel distance of the translation stage’ s X, Y, and Z axes is 400 mm, and the minimum travel distance is 25 ± 1.25 m. The mounting platform can accommodate cameras of different shapes and sizes. By controlling the movement of the translation stage, the relative position between the camera’ s target surface and the uniform light source (i.e., the integrating sphere exit port) can be adjusted. According to the EMVA 1288 standard, the relationship between the distance d from the camera target surface to the exit port and the exit port diameter D should satisfy certain conditions, and the center of the CMOS camera target surface should be aligned with the center of the integrating sphere exit port. Additionally, through literature review and actual testing, it has been found that when the distance from the integrating sphere radiation source exit plane is small ($f \leq 5$), the illuminance uniformity is poor, making it unsuitable for testing optoelectronic devices at the exit position, and the temperature at the integrating sphere exit is high, which also affects device testing accuracy. When the distance is large (f ≥ 10), the illuminance uniformity is very good, but the light intensity decreases significantly. Therefore, f = 8 is more suitable for testing astronomical CMOS cameras.

The primary function of the environmental monitoring and control section is to monitor and control the temperature and humidity inside the darkroom in real time and to measure the optical power on the CMOS camera target surface. Temperature and humidity monitoring is mainly used for measuring the temperature dependence of CMOS camera dark current and for testing performance parameters under constant temperature and humidity conditions. As mentioned above, the thermal insulation layer of the darkroom can maintain temperature stability for a short period, while the temperature and humidity monitoring system can maintain constant temperature for extended periods ($±$1°C). Temperature and humidity monitoring is accomplished through sensors that transmit data back to the computer via the network. Temperature and humidity control is jointly completed by a thermoelectric cooler, compression refrigeration unit, heater, and dryer based on data returned from the sensors, with fans used to accelerate air circulation to ensure relatively uniform temperature and humidity throughout the darkroom. The optical power received by the CMOS camera target surface is measured by an optical power meter for quantum efficiency calculations.

After the overall design and installation of the optical field generation section, darkroom, translation stage, and environmental monitoring and control section, the astronomical CMOS camera test platform is shown in [Figure 5: see original paper]. After installation and debugging, it has met the camera testing conditions specified in the EMVA 1288 standard and can be applied in actual testing.

3 Implementation of the Control System

Although the CMOS camera test system platform has been built, the equipment from different manufacturers has different interfaces and communication protocols. Using each device’ s own software would greatly increase operational difficulty and prevent coordinated operation of all equipment. Therefore, achieving integrated control of the hardware devices is essential. For convenience of integration and to facilitate future equipment replacement without affecting program operation, the power switches of the entire test system are controlled through network relays to enable remote control of the entire system. All devices are connected to a router through adapter devices, with each device assigned a fixed IP address, and then accessed and controlled through the wireless network. The design and development of the CMOS camera test system control program will integrate control commands with data storage and display, which will greatly improve testing efficiency and reduce usage and learning costs.

3.1 System Deployment

The CMOS camera test platform control program is deployed on the control computer. The translation stage, light source controller, and other devices use standard RS-232 serial communication, while the monochromator uses USB communication. These devices are connected to the switch through a serial server and USB server. The optical power meter uses TCP/IP communication and is directly connected to the switch, which is then connected to the control computer, as shown in [Figure 6: see original paper]. The control computer uses a common Windows system, and the control program is developed based on the MVC framework and C# language. Users can remotely operate the CMOS camera test system platform through the control program and monitor the system status in real time. The control program achieves remote operation of the test system platform through the local area network, using control commands and execution results to interact with the device control programs to complete the entire communication process.

3.2 Architecture Design

To complete software development in a relatively short time and to quickly meet changing test system requirements during use, an agile development approach was adopted. First, software that could meet testing needs was quickly built, and then based on usage, the implementation of existing functions was adjusted and new functions were added. During the construction of the control system, to facilitate future system upgrades and function additions without affecting existing functions, the system's coupling was reduced to improve its extensibility [8].

Since the CMOS test system is still in a developmental state, it may be necessary to replace the light source controller, adjust the temperature and humidity control system, or even change the operating system in the future. Therefore, the system architecture needs to achieve loose coupling between functions and the underlying computer technologies related to those functions. Consequently, the system architecture is divided into the interface layer, function layer, and application layer [9], as shown in [Figure 7: see original paper].

The application layer provides underlying technologies such as synchronous clocks, thread management, remote communication, and transaction processing mechanisms for implementing specific functions. The function layer describes the functions of the light source controller, monochromator, temperature and humidity control, and the relationships and interaction behaviors among various components. The interface layer is used to receive user-input data and present returned data and charts, providing users with an interactive operation interface.

To achieve separation between the application layer, function layer, and interface layer, a container-component-service model was adopted. .Net provides implementations for container components, but since many device SDK packages do not support the .Net environment due to hardware differences and performance variations, we chose to develop our own. Separating the system’ s application layer, function layer, and interface layer has the following advantages: (1) It reduces dependencies between layers, which is beneficial for later upgrades and modifications to the control system. The loose coupling between the function layer and application layer can reduce the workload of later software adjustments. (2) Developers can focus on only one layer of the entire system. When developing specific functional applications, they do not need to concern themselves with the implementation of specific technologies in the application layer, greatly reducing maintenance costs and time.

The test platform control system is deployed on the control computer. It can directly control the equipment on the test platform through the control interface on the control computer and return execution results. It can also receive instructions sent by the data computer. After receiving the instructions, the control system parses them and then executes them to indirectly control the equipment on the test platform. The control system flowchart is shown in [Figure 8: see original paper].

The control system instructions correspond one-to-one with the executable operations of the hardware devices. The test platform includes a light source controller, monochromator, three-dimensional translation stage, optical power meter, and temperature and humidity equipment. Due to the large number of devices, the control instructions are also relatively complex. Some commonly used control instructions are listed in . When the network connection is normal, the control system will receive three types of results depending on the execution of the control instructions: execution success, execution failure, and instruction error. When the network connection is interrupted, sending control instructions will return a message prompting the user to check whether the network connection is normal.

Common Control Instructions List

Instruction	Function
START/STOP	Turn on/off light source controller
A-PRESET	Set light source controller current value
FILTER	Switch filter to specified position
SetWave	Select specified grating
Shutter	Switch monochromator shutter to specified wavelength
Set X/Y/Z	Set translation stage X/Y/Z axis position
Current value	Current value
Wavelength	Wavelength
SetIntegrationTime	Set optical power meter integration time
Integration Time	Integration time
GetPeakWave	Query peak wavelength
GetPeakIntensity	Query peak intensity

3.3 Interface Design

To facilitate tester operation, a graphical user interface was designed, as shown in [Figure 9: see original paper]. The interface design is based on functional implementation and adopts a minimalist style, allowing testers to clearly understand the functions and quickly receive data information. The entire interface is mainly divided into three parts: information feedback, chart display, and device control, enabling testers to quickly understand and become familiar with the interface. The main interface only lists the functions essential for testing, such as the movement position of the translation stage and the current wavelength of the monochromator. Functions used less frequently during testing, such as device port changes, translation stage acceleration, and monochromator filter wheel settings, can be adjusted by modifying the corresponding configuration files.

3 Conclusions and Outlook

The astronomical CMOS camera test platform has functionally achieved measurement of camera performance parameters including quantum efficiency, gain, dark current, signal-to-noise ratio, dynamic range, and photo-response non-uniformity, meeting the testing conditions required by the test system. After multiple runs and debugging, the platform control system executes control instructions correctly for the power controller, translation stage, monochromator, and temperature and humidity control, with normal data return and stable chart display. The overall operation of the CMOS camera test platform and control system is stable and reliable, meeting the requirements of the test environment.

The astronomical CMOS camera test platform is still under development. During the implementation of the control system, an agile development approach was adopted, providing good extensibility that enables deployment iterations within relatively short development cycles. This lays a solid foundation for future adjustments to existing functions and addition of new functions to the test system.

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