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Research on the electronic control system for multispectral infrared detectors

Jing Yu[1], Nan Liu[2], Peng Ding[2], Zhanqiang Ru[2], Suzhen Cheng[1], Zhengguang Wang[1], Jingwu Gong[2], Zhizhen Yin[2], Fei Wu[2], Helun Song[2,3,*]

[1]School of Nano-Tech and Nano-Bionics, University of Science and Technology of China, Hefei, China
[2]Nano Device Department, Suzhou Institute of Nanotechnology and Nanobiology, Chinese Academy of Sciences, Suzhou, China

[3]hlsong2008@sinano.ac.cn
[*]corresponding author

Abstract. In order to acquire and fully exploit multispectral information of scenes, and to establish a foundation for the research of multispectral image algorithms, a laboratory has developed a multispectral infrared detector capable of detecting short-wave infrared, mid-wave infrared, and long-wave infrared in three bands. Additionally, a preliminary electronic control system has been designed. The system employs a field-programmable gate array (FPGA) to accomplish the timing control, data acquisition, preprocessing of individual channel images, and multispectral image fusion of the detector. The preprocessing involves black level correction, blind element correction, non-uniformity correction, and histogram equalization of the raw images. For trispectral fusion, color enhancement is applied to linearly combined images in the YUV color space using a color transfer method. The system utilizes a pipeline design to ensure algorithm efficiency. In simulation, the electronic control system for the multispectral infrared detector obtains trispectral information of the scenes, and through image preprocessing and fusion, enhances the understanding of scene information.

Keywords: FPGA, Multispectral Infrared Detection, Trispectral Image Fusion.

1. Introduction

Infrared radiation, situated adjacent to visible light in the electromagnetic spectrum, possesses unique characteristics. Infrared radiation can penetrate haze, smoke, and similar obstructions, making infrared detection essential for targets that are not directly observable by the naked eye or cannot be detected by other sensors. The technology of infrared detectors has emerged to capture, measure, and analyze infrared radiation.

The study of infrared technology began in the 1800s when the British astronomer F.W. Herschel discovered infrared radiation. Modern infrared technology originated in the 1940s and underwent significant development through historical phases such as the Vietnam War, Cold War arms race, and the new military revolution. Germany successfully developed active night vision devices and infrared communication equipment during World War II, laying the groundwork for the development of infrared technology. Over the years, each technological update has substantially improved the performance of infrared detectors. The earliest infrared detectors were discrete, using unit or small array detectors with a limited number of detection elements, usually numbering in the tens or hundreds. These detectors employed complex optomechanical scanning devices to obtain electrical signals from scenes, which were then processed into video signals through signal processing circuits. The first-generation infrared imaging device was the Forward Looking Infrared (FLIR) system developed in the United States, capable of recording temperature distribution of scenes in a non-real-time manner. Due to the limited number of detection elements, the performance of first-generation infrared imaging devices was lower, requiring one- or two-dimensional optomechanical scanners, resulting in slow response, complex structures, and high costs. In the early 1960s, infrared thermal imaging technology emerged but was constrained by three factors: detector performance, the environment and distance between targets and detectors, and the different spectral characteristics of various targets. In the mid-1960s, the Swedish company AGA achieved a significant breakthrough in infrared imaging technology, successfully developing the second-generation infrared imaging device. Compared to the first-generation imaging devices, the second-generation infrared imaging device could real-time record the temperature distribution of targets and detect high-speed moving targets, thus known as an infrared thermal imager. Early thermal imagers required cooling to operate, resulting in high costs and large sizes, primarily used in military applications. To expand into civilian fields, measures such as reducing scanning speed, increasing image resolution, and lowering instrument costs were implemented, gradually transforming infrared thermal imagers from military to civilian use. In the mid-1960s, the first real-time imaging system for industrial use was introduced, utilizing liquid nitrogen cooling, weighing 35 kilograms, and inconvenient to use. In the mid-1980s, infrared thermal imagers adopted advanced thermoelectric cooling methods, significantly enhancing portability. In 1988, a fully functional thermal imager integrating temperature measurement, image acquisition, analysis, modification, and data storage was introduced, marking a significant improvement in reliability, measurement accuracy, and portability.

Infrared detectors are classified into monochromatic infrared detectors and multispectral infrared detectors based on the wavelength range detected. Multispectral infrared detectors, capable of simultaneously detecting multiple bands, offer more comprehensive and detailed infrared image information [1]. Multispectral infrared detectors are typically implemented through an Infrared Focal Plane Array (IRFPA), consisting of multiple photosensitive element arrays, with each element corresponding to a different spectral band. Each photosensitive element converts infrared radiation into a charge signal, which is then processed and collected through the electronic control system. Multispectral infrared detectors hold significant potential applications in military, aerospace, environmental monitoring, medical diagnostics, and other fields. The electronic control system of FPGA-based multispectral infrared detectors combines the programmability and high integration of FPGAs with the multispectral detection capability of infrared detectors, achieving signal processing and control of multispectral infrared detectors through FPGA chips.

2. Electronic Control System of Multispectral Infrared Detector

The workflow of the system primarily involves data transmission and parsing between the upper computer (host) and the lower computer (processor), signal processing and control output by the lower computer, as well as data acquisition, processing, and transmission.

The upper computer transmits signals to the lower computer's Processing System (PS) through a USB interface. The upper computer communicates with the lower computer's PS through a USB interface, transferring signals to be processed. The upper computer is responsible for tasks such as issuing commands, setting parameters, and transferring data. Through the USB interface, reliable data transmission and communication between the upper and lower computers are maintained, ensuring accurate signal delivery and timely responses.

After parsing the signals, the lower computer's PS transfers them to the Programmable Logic (PL) side using the AXI protocol. In the lower computer's PS, upon receiving signals from the upper computer, the system initiates signal parsing and processing. The parsing process involves validating, unpacking, and decoding the transmitted data to ensure the received signals are valid and reliable.

Subsequently, the parsed signals are transmitted to the PL side of the lower computer using the AXI (Advanced eXtensible Interface) protocol, a widely used on-chip bus protocol known for efficient data transfer and communication [2].

The PL side of the lower computer selects different output modes based on control signals, sending signals to the detector and readout circuit. In the PL side of the lower computer, based on control signals received from the PS side, appropriate operating modes and parameter configurations are chosen. Depending on the control signals, the PL side can select different output paths and circuit connections to meet the operational requirements of the multispectral infrared focal plane array. The chosen output signals are transmitted to the detector and its associated readout circuit, enabling the perception of infrared radiation and signal acquisition.

The PL side controls the Analog-to-Digital Converter (ADC) to collect data signals from the detector and readout circuit. By regulating and controlling the operation of the Analog-to-Digital Converter (ADC), the PL side achieves data signal acquisition from the detector and its associated readout circuit. The ADC converts the analog infrared radiation signals into digital signals for subsequent operations, such as digital signal processing and data transmission. The PL side precisely controls and adjusts the sampling rate and accuracy of the ADC based on received detector signals and sampling clock parameters, ensuring high-quality acquisition of infrared radiation signals.

After collecting signals, the PL side processes them through non-uniformity correction, blind spot compensation, and histogram equalization before transmitting them to the DDR3 cache. In the PL side, the collected data signals undergo a series of processing and enhancement algorithms to improve image quality and enhance the clarity of target details. The process begins with non-uniformity correction, addressing response differences between different pixels to reduce spatial non-uniformity in the image. Next, blind spot compensation identifies and repairs blind or defective spots in the detector, eliminating abnormal signals during the collection process. Lastly, histogram equalization adjusts the grayscale distribution of the image to enhance contrast and details. Processed signals are then stored in the DDR3 cache, a high-speed, large-capacity memory used for temporary storage and caching of processed data.

The PS side retrieves data from the DDR3 and transmits it back to the upper computer via USB for image display. The PS side of the lower computer reads data stored in the DDR3 through a USB interface and transmits it back to the upper computer. The retrieval process involves details of data transmission and communication to ensure the integrity and accuracy of the data. Once the data is sent back to the upper computer, it undergoes image parsing, processing, and display. Through appropriate algorithms and image processing techniques, the processed data is converted into a visual image and displayed on the screen for user observation and analysis. In summary, the system workflow encompasses signal transmission and parsing between the upper and lower computers, signal processing and control output by the lower computer, data acquisition and processing, and data transmission back to the upper computer for image display. Through this process, the control system of the multispectral infrared focal plane array can achieve the collection, processing, and imaging display of infrared radiation signals in multiple bands, providing users with improved imaging results and target information acquisition capabilities.

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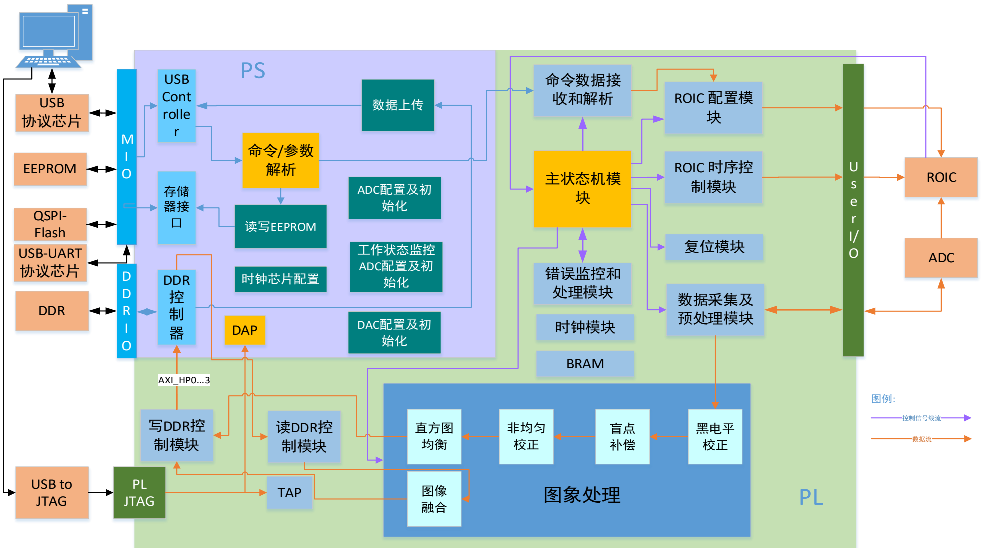

Figure 1. System Architecture Diagram

3. Module Design

3.1. Main State Machine Module

This module represents the control states of the entire lower computer system. It includes several states such as initial, reset, error, configuration, operational, and pause. State transitions are determined based on control signals from the upper computer and its internal timing. The main state machine module serves as the "brain" interfacing with the Processing System (PS), thereby controlling the entire Programmable Logic (PL) section. In the event of a system error, it halts operation, awaiting a restart.

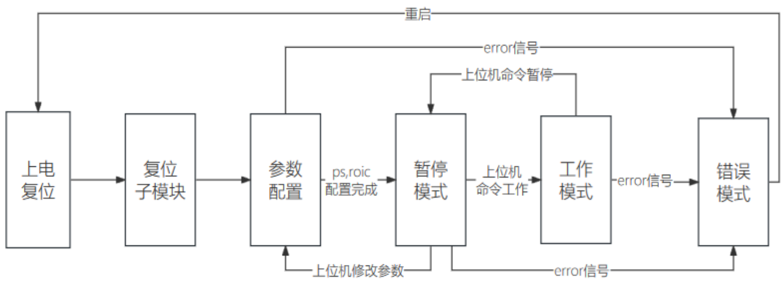

Figure 2. State Transition Diagram of the Main State Machine

3.2. Timing Control Module

The timing control module is primarily responsible for configuring the clock, band signals, and synchronization signals of the ROIC based on the output of the main state machine. The clock operates at a frequency of 10MHz, while the band signals and synchronization signals are updated every 3.3ms, corresponding to one frame update. This configuration is designed to achieve effective control over the ROIC. The timing control module adopts a parameterized design, allowing adjustment of frame synchronization time, row synchronization time, number of rows, number of columns, and other parameters to accommodate arrays of different scales.

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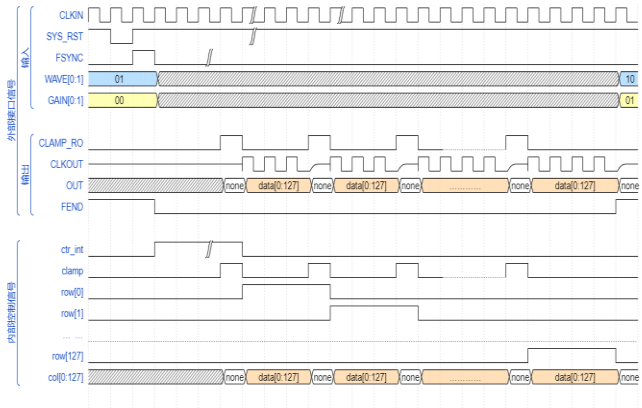


Figure 3. Timing Diagram for Readout Circuit

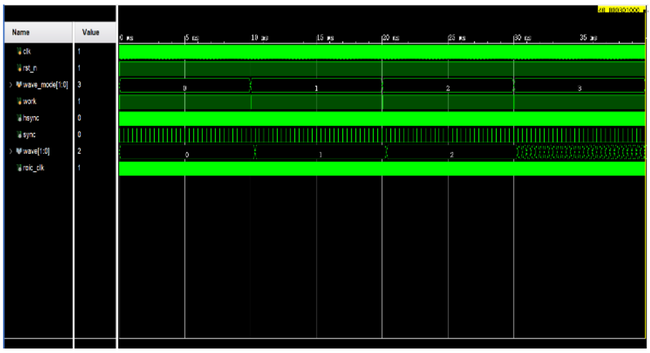


Figure 4. Timing Control Output in Vivado Simulation

3.3. Data Acquisition and Preprocessing Module

The AD9257 is chosen for sampling, with a valid time for readout circuit column output of 100ns and an ADC sampling rate of 40M, meeting the requirements. The data acquisition module can perform preprocessing based on signals from the upper computer. This involves multiple acquisitions of outputs from the same pixel, with the option to configure the number of acquisitions, and the final output is the averaged result.

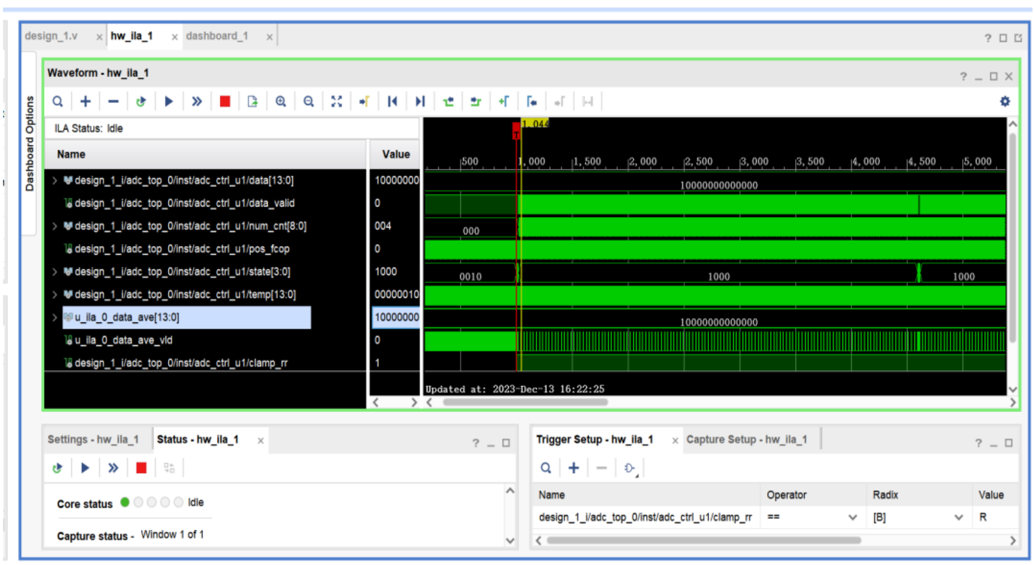


Figure 5. Experimental Diagram of ADC Data Acquisition Sampling

3.4. Image Preprocessing

The original images obtained for the short-wave infrared band, mid-wave infrared band, and long-wave infrared band are 14 bits. To optimize image quality and facilitate subsequent image fusion, it is necessary to preprocess each channel's image by eliminating blind elements, dark current noise, and device non-uniformity noise. Additionally, brightness adjustments are made through histogram equalization. The preprocessing steps include: Black Level Correction: In the absence of illumination, black images may not register as 0 numerically. To address this, an average value is subtracted, bringing the numerical values of pure black images back to 0. Blind Spot Correction: The implementation of correction techniques typically involves two stages: detection and correction. In the detection stage, algorithms analyze the raw image data output by the sensor, identify abnormal pixels, and then, in the correction stage, repair these abnormal pixels using methods such as interpolation based on the values of surrounding normal pixels [3]. Non-uniformity Correction: The chosen method is based on a two-point calibration method calibrated against a black body. Its advantages lie in its simplicity, low computational load, and high correction accuracy. Finally, histogram equalization is applied to the infrared images to balance their brightness, ensuring a more uniform luminosity [4].

3.5. Image Fusion Module

For the fusion of images in the short-wave infrared + mid-wave infrared and long-wave infrared bands, a natural color fusion algorithm based on YUV color transfer is employed [5]. The algorithm diagram is depicted in Figure 6:

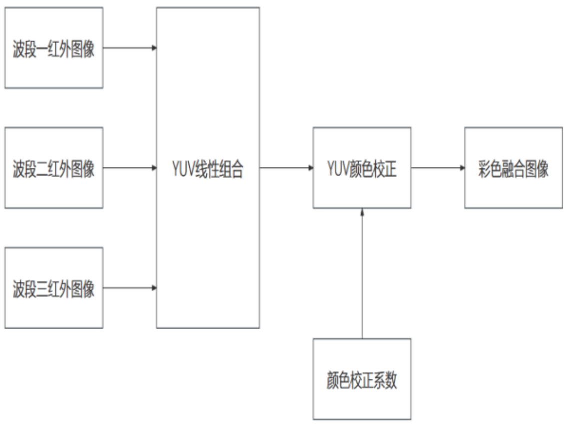


Figure 6. Diagram of Natural Color Fusion Algorithm

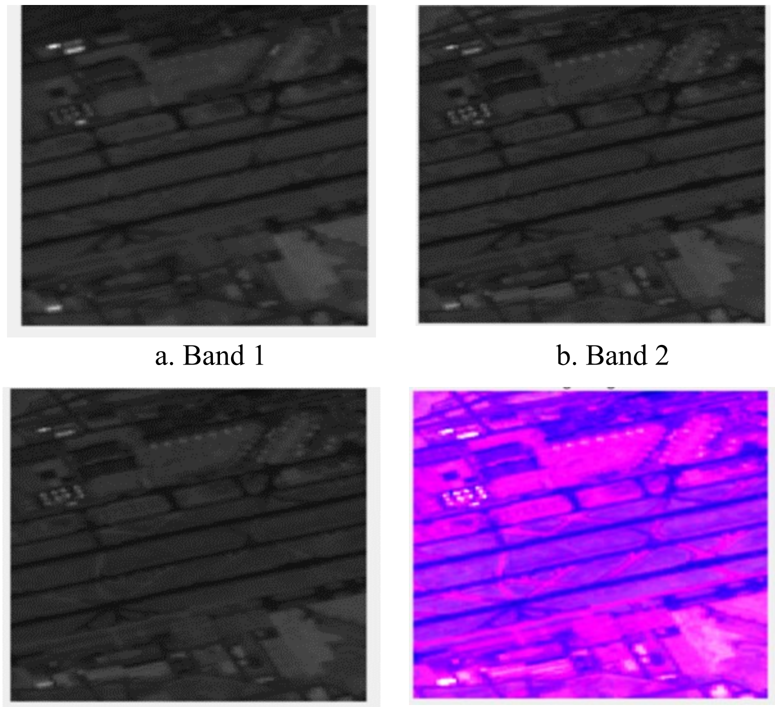
The linear combination structure is a simple and effective color fusion processing algorithm. This algorithm achieves the initial colorization of the original three-channel images in the YUV space through linear combination:

$$Y_i = k_1 \cdot \max(S_{WIR}, M_{WIR}, L_{WIR}) + k_2 \cdot \text{mid}\ (S_{WIR}, M_{WIR}, L_{WIR}) + k_3 \cdot \min(S_{WIR}, M_{WIR}, L_{WIR})$$
$$U_i = m_1 \cdot S_{WIR} + m_2 \cdot M_{WIR} + m_3 \cdot L_{WIR}$$
$$V_i = m_4 \cdot S_{WIR} + m_5 \cdot M_{WIR} + m_6 \cdot L_{WIR}$$

Where $S_{WIR}, M_{WIR}, L_{WIR}$ are the grayscale images of the short−wave, mid−wave, and long−wave infrared, and $k_1, k_2, k_3, m_1, m_2, m_3, m_4, m_5, m_6$ are nonzero rational numbers. The color of the reference image is then transferred to the initial colorized image, resulting in:

$$Y_0 = (Y_i - \mu_{i,Y})\sigma_{T,Y}/\sigma_{i,Y} + \mu_{T,Y}$$
$$U_0 = (U_i - \mu_{i,U})\sigma_{T,U}/\sigma_{i,U} + \mu_{T,U},$$
$$V_0 = (V_i - \mu_{i,V})\sigma_{T,V}/\sigma_{i,V} + \mu_{T,V}$$

Where $\sigma_{T,Y}, \sigma_{T,U}, \sigma_{T,V}$ 和 $\sigma_{i,Y}, \sigma_{i,U}, \sigma_{i,V}$ are the standard deviations of each channel for the color reference image and the initial color image, respectively. $\mu_{T,Y}, \mu_{T,U}, \mu_{T,V}$ and $\mu_{i,Y}, \mu_{i,U}, \mu_{i,V}$ are the means of each channel for the color reference image and the initial color image, respectively. The resulting natural color fusion image based on color transfer is shown in the figure:



a. Band 1　　b. Band 2

c. Band 3　　d. After Fusion

Figure 7. Natural Color Fusion Images

4. Conclusion

This paper primarily presents the development process of an electronic control system with unique three-band imaging capabilities, enabling free switching between short-wave infrared, mid-wave infrared, and long-wave infrared. By employing FPGA technology, the system accomplishes image preprocessing and three-band image fusion tasks, realizing real-time acquisition of registered three-band image sequences and fused three-band image sequences. This innovative design provides a robust platform support for the research of multi-band image processing algorithms.

Throughout the research, we expanded the dual-band natural color fusion algorithm to three bands, proposing a novel multi-band image processing solution. To enhance the imaging quality of each channel, optimization methods such as black level correction, blind spot correction, two-point non-uniformity correction, and histogram equalization were employed. Additionally, we utilized the natural color fusion method to merge the three-band images. Specific steps include linearly combining the three-band images in the YUV space to obtain the initial colorized image, followed by transferring the color of the reference image to the initial colorized image for colorization.

Through this design, we successfully developed a powerful and user-friendly three-band imaging electronic control system. This system not only provides a new research platform for the field of multi-band image processing but also lays the foundation for the application of infrared imaging technology in various domains. In the future, we will continue to optimize the system, enhance its performance and stability in practical applications, and make greater contributions to the development of infrared imaging technology in our country.

The main innovation of this study lies in the design of an electronically controlled system capable of three-band imaging, achieving free switching between short-wave infrared, mid-wave infrared, and long-wave infrared. The use of FPGA technology for image preprocessing and three-band image fusion significantly improves the system's real-time performance. Furthermore, by extending the dual-band natural color fusion algorithm to three bands, a new multi-band image processing approach was proposed. The imaging quality of each channel was optimized through black level correction, blind spot correction, two-point non-uniformity correction, and histogram equalization. The natural color fusion method was employed to merge the three-band images, achieving colorization. This study provides a new research platform for the field of multi-band image processing and holds broad prospects for applications.

In future research, we will continue to strive for optimized system performance, improved imaging quality, and real-time capabilities. Additionally, we plan to delve into more efficient multi-band image processing algorithms to further enhance the system's processing capabilities. Exploring new image fusion methods to achieve higher-level fusion is another direction of our research. Ultimately, applying this system to real-world scenarios will actively contribute to the development of infrared imaging technology in our country. These future efforts will help propel the widespread application of multi-band infrared imaging systems in different fields.

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Primary Affiliation: School of Nano-Tech and Nano-Bionics, University of Science and Technology of China

(Address: 96 Jinzhai Road, Hefei, Anhui Province, Postal Code: 230026)

Second Affiliation: Suzhou Institute of Nanotechnology and Nanobiology, Chinese Academy of Sciences