Design of data acquisition system and algorithm research for omnidirectional gamma-ray positioning equipment *

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Abstract: This article introduces the design and performance of the data acquisition system used in an omnidirectional gamma-ray positioning system, along with a new method used in this system to obtain the position of radiation sources in a large field. This data acquisition system has various built-in interfaces collecting, in real time, information from the radiation detector, the video camera and the GPS positioning module. Experiments show that the data acquisition system is capable of carrying out the proposed quantitative analysis to derive the position of radioactive sources, which also satisfies the requirements of high stability and reliability.

Key words: gamma-ray positioning, data acquisition, FPGA

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1 Overview

Although nuclear science and technology bring great benefits to human life, improper use or disposal of radioactive materials may lead to social and personal property losses and create social panic. In order to solve this problem, gamma ray detection and positioning techniques are used to monitor radioactive materials in the environment. This radiation monitoring equipment can usually only position the sources in 360 degrees horizontally; no commercial products are currently available that can locate the sources in all dimensions. Therefore, we propose a system with full coverage of multiple points in three dimensions, which can process and respond to the data from multiple sources, make the right decision immediately and locate the radiation sources in large areas in three dimensions. Network detection and multiple detection units are used in this system, each detection unit in different positions is able to acquire and process information efficiently and independently. For this omnidirectional gamma ray positioning equipment integrated with optical imaging interfaces, a GPS module interface and wireless transmission interfaces, a data acquisition system is designed to provide all necessary information in all dimensions to the central system, which can then evaluate the location and direction of the radiation via the positioning algorithm presented in Section 4. Experiments show that this system can work stably in all kinds of environments.

2 System architecture

The omnidirectional positioning system is mainly composed of several radiation detection and imaging units and a remote control center [1]. As shown in Fig. 1, each detection unit has three parts: the fast positioning module, the precise positioning module and the data acquisition system. The fast positioning module is capable of 3D detection and positioning, which preliminarily evaluates the location of radiation via static measurement. The precise positioning module [2] locates radiation hot spots by accurate 2D "photo-taking" and relative position calculation. The data acquisition system connected to both detection modules processes the detected signals about radiation sources and the environment from multi-channel detecting units.

3 Data acquisition system design

3.1 Hardware design

The data acquisition system functions to collect information from the fast positioning module and the precise

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positioning module, along with multiple real-time environmental parameters in the same detection unit. Each unit can process information independently. The main structure of the hardware design is shown in Fig. 2, in which a serial multi-channel analog-to-digital converter (ADC) chip and FPGA [3] (Field Programmable Gate Array) are adopted to process data at high speed. Other hardware includes DDR (double data rate synchronous dynamic random access memory), local bus controls and a variety of interfaces.

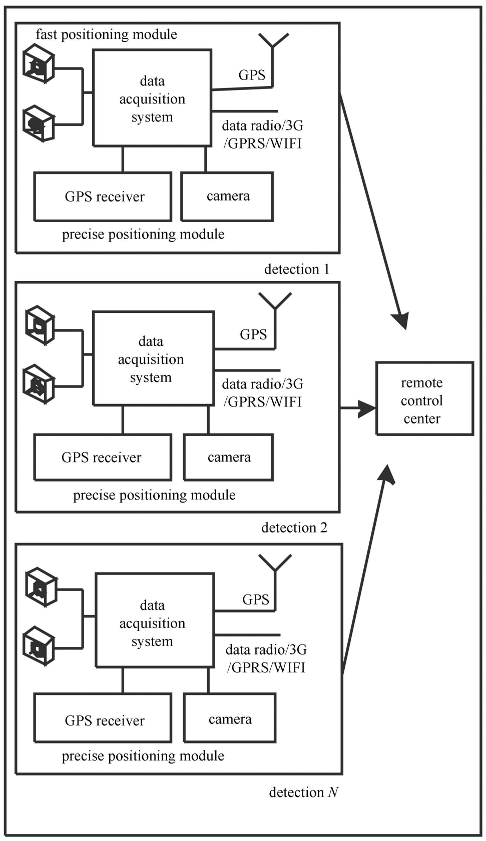

Fig. 1. System structure of the omnidirectional gamma ray system.

The interfaces include an optical imaging interface, a GPS module interface and a wireless transmission interface. The optical imaging [4] interface obtains optical images of the environment in order to identify the location of the radiation source, constituting a part of the precise positioning module in the detection unit. The GPS module interface provides auxiliary parameters for the positioning algorithm, which accurately determines the incident angle of the radiation source and calculates its location. The wireless transmission module is an interface between the data acquisition system and the remote control center. A variety of optional interfaces can be adopted flexibly for different applications, such as cable connection, WIFI, [5] 3G/2G connection and data radio.

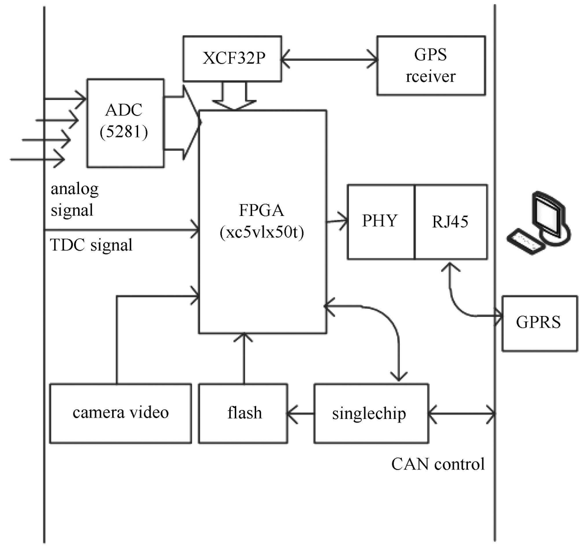

Fig. 2. Hardware structure of data acquisition system.

3.2 Software design

The software design of the data acquisition system is mainly implemented in FPGA, which processes the data from multiple interfaces; the flow chart is shown in Fig. 3. Firstly, the FPGA controls the ADC by accessing its internal registers through the serial bus. Secondly, the signal pulse output from the ADC is processed to determine the hit position and the energy of gamma photons. During this process, the serial data are first desterilized, then the baseline is restored digitally and integrated digitally before the position (x, y) of and the energy (E) of the target gamma photon hits can be derived. Information about the crystal number and energy mark can be obtained by looking up the location table and energy table stored in the FLASH. Thirdly, FPGA also reads data from external interfaces, such as the longitude, latitude and time information from the GPS module and the optical information from the video camera. Finally, the FPGA puts all these data in the gigabit network interface for either wired or wireless transmission according to the requirement of various applications.

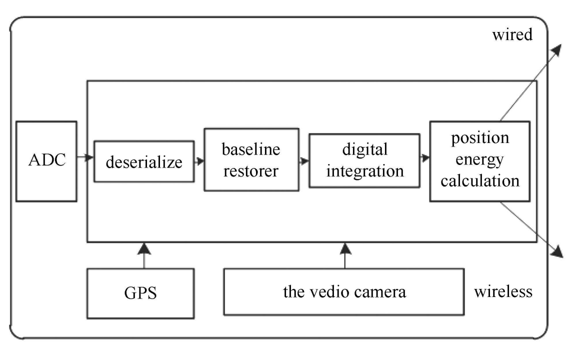

Fig. 3. Structure of the FPGA software.

4 Positioning algorithm

In order to calculate and analyze the position of radiation sources on the full scale, the fast positioning module first obtains information about the latitude and longitude, time and the hit count on the crystals in real time and figures out a rough direction and geographical position of the radiation sources in all dimensions. Then the precise positioning module moves closer to the radiation source and gets the image of the radiation hot spots in the 2D "photographs" mode.

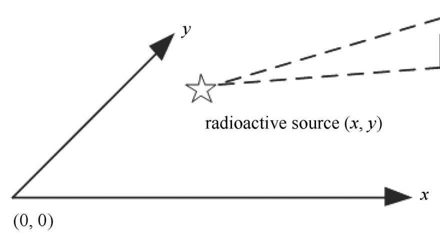

Fig. 4. Positioning on the horizontal plane with single layer crystal array.

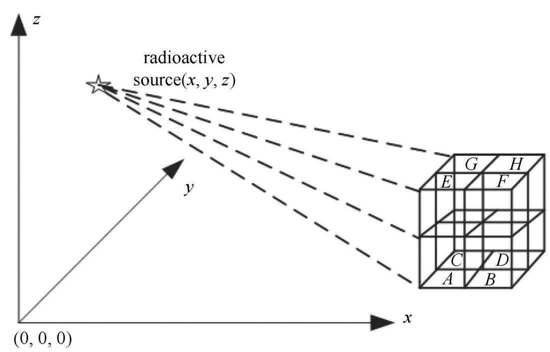

Fig. 5. Positioning in three dimensions with double layer crystal array.

As crystals can resist some of the gamma rays, the hit counts on them depend on the position of the radiation source. If a single layer crystal array is used in the fast positioning module, the detection efficiency of each crystal in the detection unit changes significantly when the source moves in the horizontal plane, but they are insensitive to movements in the vertical plan; However, in our design, a double layer crystal array is used so that the changes of source location in both horizontal and vertical planes can be detected efficiently, thereby realizing 4π solid angle positioning, as shown in Fig. 4 and Fig. 5.

The detection units/detectors are arranged at N ($N \geqslant 3$) tentative points in a 3D coordinate. The positioning method is introduced by taking three points as an example, as shown in Fig. 6. Point A is the true origin and the distance between A and B is L, equal to that between A and C. These three points form a right angle in the horizontal plane.

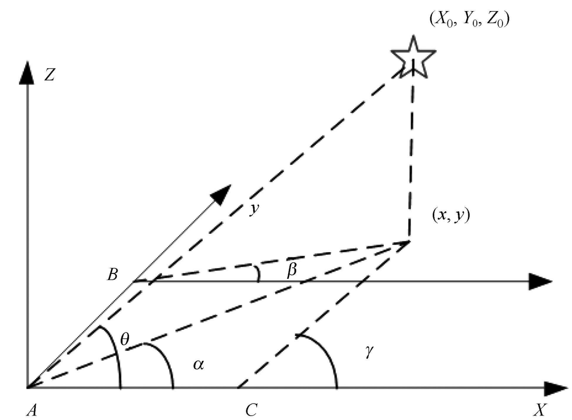

Fig. 6. Diagram of positioning solid angle gamma ray in all directions.

The fast positioning module in each detector at the three points calculates the relative incident angle of the arriving ray. The source of the radiation is located at (X_0, Y_0, Z_0) and its projection in the X, Y coordinate plane is point (x, y). The straight line passing through this point and point A, B, and C respectively makes an angle α, β, γ with the X axis in the X, Y coordinate plane. In 3D coordinates, the line passing the origin A and the radiation source makes an angle θ with the X axis.

The angles mentioned above can be derived as follows: the hit counts on the crystal (A, B, C, D) from different incident angles have been simulated, pre-stored and grouped by every 2°, i.e. (A_0, B_0, C_0, D_0), (A_2, B_2, C_2, D_2)$\cdots$(A_{358}, B_{358}, C_{358}, D_{358}). For the actual experimental data of (A, B, C, D), the absolute value or the square root of the distance between it and each pre-stored datum is calculated, as shown in Eq. (1); therefore, from the minimum distance, the closest incident angle to the horizontal plane is derived.

$$\begin{cases} s_0=\sqrt{(A-A_0)^2+(B-B_0)^2+(C-C_0)^2+(D-D_0)^2} \\ s_2=\sqrt{(A-A_2)^2+(B-B_2)^2+(C-C_2)^2+(D-D_2)^2} \\ s_4=\sqrt{(A-A_4)^2+(B-B_4)^2+(C-C_4)^2+(D-D_4)^2} \\ s_6=\sqrt{(A-A_6)^2+(B-B_4)^2+(C-C_6)^2+(D-D_6)^2} \\ s_{358}=\sqrt{(A-A_{358})^2+(B-B_{358})^2+(C-C_{358})^2+(D-D_{358})^2} \\ \mathrm{MINS}=\mathrm{MIN}(S_0,S_2,S_4,S_6,\cdots,S_{358}) \end{cases}. \tag{1}$$

Similarly, the incident angle to the vertical plane at the origin can be derived from the crystal A, B, E, F in the vertical direction, as shown in Fig. 5.

Finally, the direction and relative position of the radiation source is determined rapidly from geometric relations combining the geological location (longitude, latitude) acquired in the detection unit with the α, β, γ, θ angles, as shown in Eqs. (2) and (3).

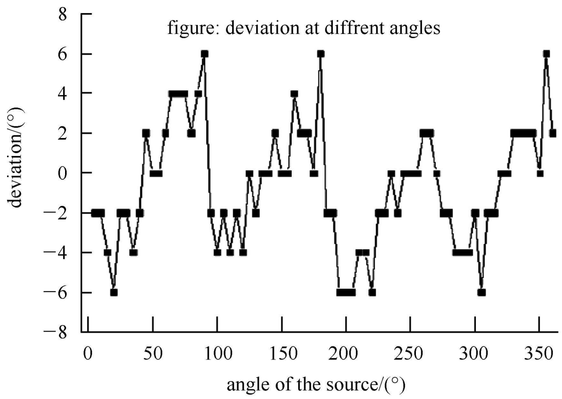

Fig. 7. The incident angle accuracy.

Statistical deviation leads to the fluctuation of the calculated angle of incidence within $\pm 6°$, as shown in Fig. 7, but this range of deviation is acceptable in determining the position of the radiation source relative to the detectors.

$$\begin{cases} X_0=\dfrac{L}{\mathrm{tg}\alpha-\mathrm{tg}\gamma} \\ Y_0=\dfrac{L\cdot\mathrm{tg}\alpha}{\mathrm{tg}\alpha-\mathrm{tg}\gamma} \\ Z_0=\sqrt{(X_0^2+Y_0^2)}\mathrm{tg}\theta \end{cases} \left(-\frac{\pi}{4}\leqslant\alpha<\frac{\pi}{4},\frac{3\pi}{4}\leqslant\alpha<\frac{5\pi}{4}\right), \quad (2)$$

$$\begin{cases} X_0=\dfrac{L\cdot\mathrm{tg}\beta}{\mathrm{tg}\alpha-\mathrm{tg}\beta} \\ Y_0=\dfrac{L\cdot\mathrm{tg}\alpha\cdot\mathrm{tg}\beta}{\mathrm{tg}\alpha-\mathrm{tg}\beta} \\ Z_0=\sqrt{(X_0^2+Y_0^2)}\mathrm{tg}\theta \end{cases} \left(\frac{\pi}{4}\leqslant\alpha<\frac{3\pi}{4},\frac{5\pi}{4}\leqslant\alpha<\frac{7\pi}{4}\right). \quad (3)$$

5 System performance

A prototype equipment of the proposed omnidirectional gamma ray positioning system shown in Fig. 8 is tested at room temperature and an extremely low temperature, including the network test, flood image test, energy spectrum test and positioning test. In the experiment, a ^{22}Na point source with a diameter of 0.5 mm and activity of 3 MBq, rotates around the detector at the speed of $2°$/sec, which then moves vertically. The result generated with the LABWINDOWS software is displayed in Fig. 9,

Fig. 8. Picture of the prototype equipment.

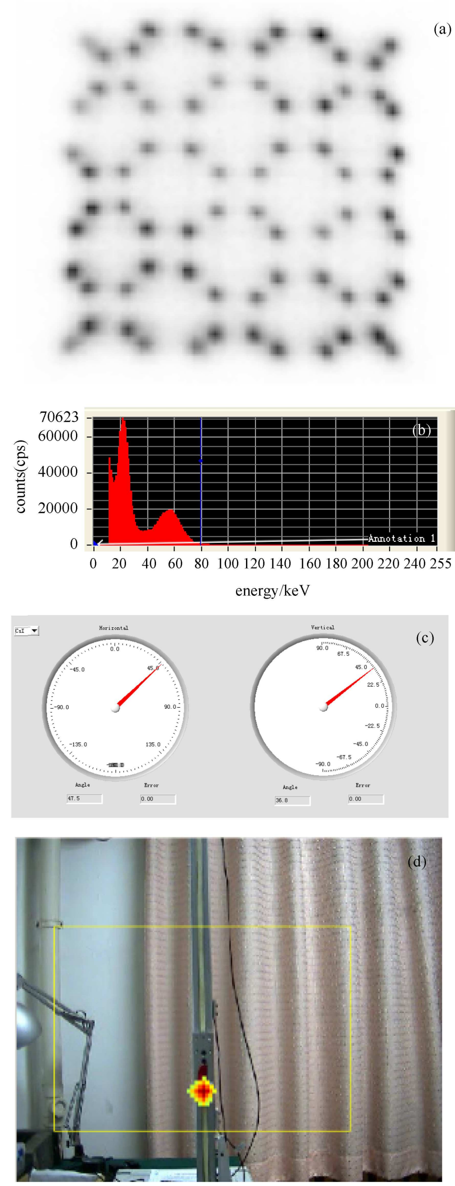

Fig. 9. The experimental results. (a) The flood image, (b) the spectrum, (c) the incident angle of radiation source in horizontal /vertical direction, (d) the fusion image.

where (a), (b), (c) and (d) are the flood image, energy spectrum, incident angles and fusion image respectively. The flood image and energy spectrum are statistical results of the digital processing of the detected signals. The former indicates that the data acquisition system has perfect spatial resolution, while the latter shows that the main energy peak and low energy scattering peaks can be distinguished clearly in the spectrum so that the nuclide can be identified. Figs. 9(c) and (d) give the results of the position and image of the radiation source.

6 Application

In addition to performance testing in the laboratory, the omnidirectional gamma ray positioning system is also applied in some practical scenarios. As shown in Fig. 10, an abnormal radioactive dose is detected in a radiation source storage place by long-term dose monitoring. Although it is very difficult to locate the precise position of the source with handheld dose devices because of the obstacles on site, the proposed omnidirectinal gamma ray acquisition system can quickly locate the position of the radiation source and take an image of it with the precise positioning module.

Fig. 10. Searching for radiation source with the precision positioning module.

This result demonstrates that the proposed system can locate in a few seconds the position of the radiation source whose activity is below the mCi level. For example, the device can obtain in 10 seconds the image of a mouse having been injected with 3.7×10^{-7} Bq ^{18}F drug in a PET machine within 6 meters away (Fig. 11). The data acquisition system completes information acquisition and processing in real time.

Fig. 11. Quick positioning the mice.

7 Conclusion

The proposed data acquisition system for an omnidirectional gamma-ray positioning system with integrated multiple information interfaces is designed modularly and characterized by mobility, flexibility and portability. The proposed positioning algorithm implemented in this system is proved to be capable of locating the ray source rapidly with 4π solid angle and measure its distribution intensity. Experiments show that the proposed omnidirectional gamma-ray positioning system is suitable for quick analysis of a radiation source in a large field.

References

1 Leadbeater T W et al. Nucl. Instrum. Methods A, 2009, **604**: 355

2 ZHANG Yu-Xuan et al. The System Design, Engineering Architecture and Preliminary Results of a Lower-cost High-sensitivity High-resolution Positron Emission Mammography Camera. Proc. of 2008 IEEE Conf. on Nuclear Science Symposium. Dresden: IEEE Conference, 2008. 794

3 http://www.xilinx.com/support/documentation/user_guides/ug190.pdf

4 Kaddachi M L et al. FPGA-based Image Compression for Low-power Wireless Camera Sensor Networks. Proc. of the 3rd Int'l. Conf. on Next Generation Networks and Services. Hammamet: IEEE Conference, 2011. 8

5 XIN Yu-Niu et al. Reconfiguring Distributed Applications in FPGA Accelerated Cluster with Wireless Networking. Proc. of the 21st Int'l. Conf. on Field Programmable Logic and Applications. Chania: IEEE Conference, 2011. 545