Automatic control and detection systems for low-level radioactive waste drums

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Abstract: Vast quantities of low-level solid nuclear wastes are produced in the operation and decommissioning of nuclear facilities. These radioactive nuclear wastes are usually contained in special drums. Consequently, these nuclear waste drums must be tested, classified and their levels measured before they are placed in a final repository. There are certain dangers during the detection process; there is an urgent need for a safe, efficient, and autonomous system to inspect these nuclear waste drums. This study describes the methods involved in scanning and measuring the vertical section of radioactive waste drums and describes using the programmable logic controller (PLC-SIEMENS S7-1200) in order to construct an automated system as well as a detection system. According to the waste drum test flow, we designed a control program that utilizes the STEP7 Software as well as a monitoring program using SIEMENS WinCC that is flexible within the computer’s central monitoring system. In the future, this system may be applied beyond the scale of a laboratory; nuclear enterprises may be able to adopt this process for sampling checks on contaminated waste. This study ensures the detection efficiency of waste drums as well as the safety of their operators. Furthermore, the proposed system effectively promotes the disposal and management of radioactive waste, which has potential applications in engineering.

Keywords: Detector control systems (detector and experiment monitoring and slow-control systems, architecture, hardware, algorithms, databases); Detector alignment and calibration methods (lasers, sources, particle-beams)

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1 Introduction

As nuclear power continues to develop in China, a significant quantity of solid nuclear wastes is produced as a consequence in the decommissioning of Nuclear Facilities. These wastes often emit ionizing radiation and are composed of radioactive nuclides, seriously threatening human health. Therefore, in order to mitigate the risks associated with these radiation levels, adequate management of nuclear waste must be done [1, 2]. According to China’s Regulations on Radioactive Waste Management, nuclear waste must be classified and verified in accordance with the Classification Standards of Radioactive Waste. This circular is forwarded to waste deposit sites prior to the confirmation of low-level solid nuclear wastes in China [3, 4].

Low-level solid wastes are usually produced by nuclear facilities, which belong to medium and low-density non-uniform radioactive wastes. This type of radioactive waste is also deposited in special drums. Currently, the analysis and measurement of special waste drums involve two methods: SGS (Segmented Gamma Scanner) and TGS (Tomographic Gamma Scanning), which both utilize the same gamma spectrum [5, 6]. SGS is simpler and faster than TGS and is a non-destructive form of analysis used in the quantitative analysis of nuclear waste. SGS may avoid the long time DA (destructive analysis) in nuclear waste drums and does not produce secondary radioactive wastes while measuring [7, 8].

We employ SGS technology [9–11] in the detection of waste drums in this study. According to the principles of measurement of SGS, all sorts of waste with low-density and non-uniformity are scanned in vertical section and horizontal rotation. The gamma spectrum is obtained from the transmission source as well as the radioactive waste itself to correct the effect of gamma
ray self-absorption in waste drums. To ensure the quality of measurement, the waste drum is positioned accurately among the SGS equipment. The transmission source and detector may both be positioned automatically, and their positions should be correlated on the same horizontal line. In order to ensure the safety of the inspectors from the radiation emitted from the waste drums, it is necessary to decrease the measurement time, ensure accurate positioning, and exercise reliable measurements via an automatic control system. Therefore, automating SGS may provide a reliable degree of guarantee.

In the 1970s, J.L. Parker introduced segmented gamma scanning (SGS) technology in the Los Alamos National Laboratory in the United States. In the 1980s, SGS was developed to maturity [12]. Then, in 1994, SGS technology was brought and developed in China. The computer control system achieved a high level of automation, but its control accuracy was low. With the development of automation technology, the control accuracy requirements of the system become increasingly higher. Improving the control accuracy as well as the control speed is conducive in improving the quality of SGS detection [13, 14]. This study presents a control system based on a programmable logic controller (PLC), a high-precision controller. Moreover, an automatic control system of the mechanical transmission bench is designed and is comprised of a multi-dimensional structure, including horizontal movements, rotating equipment, radioactive source lifting and vertical lifting of detectors. The system adopts PLC to control the four types of movements [15, 16]. PLC is widely used in the process control, and it is both stable and reliable and may be used for accurate positioning. Furthermore, PLC may realize the automatic detecting system of low-level radioactive waste drums by improving the efficiency of the waste drum’s detection. We chose the core PLC to be the SIEMENS S7-1200 using the STEP7 platform, and its programming language was a ladder diagram or statement list. Man-machine interfaces use programmed WinCC flexible software. The present system is qualified and may be widely applied in laboratories and nuclear enterprises in the future.

2 Detection: principles and methods

2.1 Key detection principles

The detection of nuclear waste drums is usually carried out via gamma ray measurement. This method utilizes various characteristics of gamma rays to analyze the radioactive waste and considers the intensity of gamma rays to calculate the content of the radionuclides. This experimental assembly consists of an external standard gamma source, a waste drum, and a high-purity germanium (HPGe) detector on opposite sides. The HPGe detector is the ORTEC(R) [Model GEM-MX7080P4-HE-SMP] (U.S.A.). It is a P-type coaxial detector. The diameter of the detector crystal measures 70 mm, and the length is 82.6 mm. The detector bias voltage is 2600 V, and the energy response range is 10 keV to 10 MeV. The detector possesses a relative detection efficiency of 66% at 1.33 MeV with an energy resolution of 0.15%.

During testing, the drum is placed on the rotating platform. The detector then scans the entire field within the rotating, and measures the intensity change using gamma-ray transmission and determines the self-absorption coefficient of the material. The data acquisition process utilizes parallel beam geometry. A solid angle model is established according to the opening angle among
the triadic relationship, so that the gamma ray correction factor for self-attenuation in sample CF (AT) of the waste drum may be accurately computed.

Assuming that the radioactive nuclear waste drum is cylindrical in shape and the diameters of nuclear waste drum are far smaller than that of the radioactive nuclides and detectors, we may calculate the CF (AT) using the self-absorption correction coefficient formula for the solid angle model.

The formula is shown below [17]:

\[
\begin{align*}
\text{CF} (\text{AT}) &= \frac{1}{2} \left[ B_1 \left[ -\ln(T) \right] - S_1 \left[ -\ln(T) \right] \right] \\
T &= \exp(-\mu' D)
\end{align*}
\]

(2.1)

(2.2)

Where, \( D \) is the diameter of the radioactive waste drum. \( \mu' \) is the linear absorption coefficient. \( B_1 \) is linear terms of Bessel function. \( S_1 \) is linear terms of Struve function.

However, the nuclear waste drum does not usually meet the conditions in the actual measurement. Instead, it is close to the solid angle and adopts a three-dimensional self-absorption model. Assuming the radiation to be uniform, the correction factor for self-attenuation in sample CF (AT) is shown below:

\[
\begin{align*}
\text{CF} (\text{AT}) &= \iiint \exp\left[ -\mu'_c (r_1^2 - r_2^2) \right] \frac{r \, dr \, d\theta \, dz}{2} \\
\int \exp\left[ -\mu' (r_2^2 - r_1^2) - \mu' r_1 \right] \frac{r \, dr \, d\theta \, dz}
\end{align*}
\]

\[
\begin{align*}
-\mu' &= -\frac{\ln(T)}{D_1} \\
\mu'_c &= -\frac{\ln(T_c)}{D_3 - D_2}
\end{align*}
\]

(2.3)

(2.4)

(2.5)

Where, \( \mu' \) is the linear absorption and \( \mu'_c \) is the linear absorption of drum. \( \lambda \) is the distances of waste drum and detector. \( T \) is the transmissivity of nuclide, and \( T_c \) is the transmissivity of drum. \( D_1 \) is the diameter of the nuclide, \( D_2 \) is the internal diameter of drum and \( D_3 \) is the external diameter of drum.

According to the various geometric parameters of the detector’s open solid angle, the CF (AT) using the three-dimensional numerical integral method is calculated accurately.

The principle of segmented gamma scanning is used to obtain a series of calibrations that is able to determine the characteristics of a radionuclide with gamma-ray observation. The researchers now have an established relationship between the observed and corrected counting rates of gammarays as well as the quality of the known nuclides. Considering the corresponding rate of loss of the counting rate and the attenuation of the scan contrast in each section, we correct the all-section counting rate. The total count rate as well as the direct proportional relation of the measured nuclides in all of the segments were obtained within the range of angle phase between detector and sample. We use the actual method for waste analysis to calibrate the same steps and conditions.

A correction counting rate curve is then obtained by using multiple lines at different levels of energy. This curve considers the losses in count rate of the gamma-ray spectrum measurement and calculates the all-around peak counting rate of n section in the energy gamma-ray.
The formula is shown below:

\[ CR_n = RR_n \times CF_n (AT) \]  

(2.6)

Where, \( CR_n \) is \( n \) section sample detection of revised full-energy peak count of gamma ray. \( RR_n \) is the \( n \) section sample detection of original full-energy peak count of gamma ray.

It calculates the nuclides activity of the nuclear waste drum using the formulas (2.7) and (2.8).

\[ TCR = \sum_n CR_n \]  

(2.7)

\[ A = \frac{TCR}{K \times R} \]  

(2.8)

Among the represented formulae, \( TCR \) is the total count rate of radionuclides, \( A \) is the activity of the radionuclide, \( R \) represents the gamma-ray branching ratio with radionuclide launching energy, and \( K \) signifies the scale factor, which is related to the detector efficiency, the gamma-ray energy being measured as well as the measured radionuclide solid angle of the gamma detector.

2.2 Current methods of detection

In regard to modern methods of detection of waste drums, a standard gamma source is placed on one side as the transmission source while positioning the lead shield at the front. The external standard gamma source used is \(^{60}\)Co and \(^{137}\)Cs. The experimenter places a \(^{60}\)Co source in front of the detector endcap and sets the main amplifier gain to achieve a pulse height of 8 to 9.5 V for the 1.33 MeV line, as measured. Instead of using a \(^{137}\)Cs source, we attained a pulse height of 5 V at the 661.661 KeV line. The researchers then placed the standard waste drum in the center. Accordingly, gamma rays passed through the waste drum, and the signal was received by a parallel detector. The detector itself is equipped with a flat collimator at the front, which is made of lead and determines the horizontal and vertical visual angles of the detector, shielding itself from the surrounding radiation.

Simultaneous detection of the waste drums using multiple sources and detectors is usually adopted. Radioactive sources and detectors are vertically placed on the both sides of the detected waste drum, and each unit performs rapid detections at the same horizontal plane. An advantage to this method is that the detection time is quick, however, there are overlaps in measurement and the precision is lower. Another technique is to use a radioactive source and multiple detectors to attain more accurate detection. The radioactive source is located at the end of the waste drum and multiple detectors form fan-shaped positions on the opposite side. These devices need to be placed on the same plane. This method is advantageous due to its high accuracy and favorable quality. However, there is no economic benefit given the high cost of the detector.

For this experiment, the detection method used a single source and a single detector. Radioactive sources and detectors are placed on the platform, which is driven by an AC servo motor. The device first runs to the specific locale, then detects at corresponding multiple locations. The specific location is controlled via computer program. The AC servo motor’s power adequately meets the requirements for rapid detection. The advantage of this method is the use of a single detector, which is more economical. Moreover, this method may be used to detect a single position in order to satisfy the accuracy and quality for various times. Its main purpose is to reduce the visual angle and
improve attenuation correction deviation, which contributes to the final overall effect. A high-purity germanium detector is used, which was produced by the company, ORTEC®, U.S.A.. It uses the waste drum of approximate homogenization samples to fill and design a rotation device for the test. This enables the waste drum to rotate at a constant speed of ten revolutions per minute, which can be altered.

The basic structure of the system is shown in figure 1. The nuclear waste drum is standard size. The size of the nuclear waste drum is that the volume is 400L, the inner diameter is 700 mm, the external diameter is 772 mm, and the high is 1132 mm.

![Figure 1. The basic structure of the system.](image)

3 System design

In the waste drum detection control system, the SIEMENS [Model S7-1200] PLC was used as the core controller, which provided two operation plats: electrical cabinets and touch screen controls. These two operation plats both communicate with the PLC and may alter the corresponding effective information. This system is controlled by four servomotors; one motor manages the horizontal movement, carrying the waste drum, while the other one handles rotation. The final two motors are used for positioning and speed and carry the standard source and detector, respectively [18].

The system consists of four parts: the horizontal motion device driver, rotated plat driver, detector lifting gear driver and the sources’ lifting gear driver. The structure and configuration of the system are shown in figure 2. The arrow represents the path of data transmission. Two-way arrow represents that the data can be transmitted in both directions, and one-way arrow can only be transmitted in one direction.

There is an electrical control system and four mechanical devises in figure 2. The electrical control system is mainly composed of PLC controller, monitoring computer, manual operation panel and power supply system, and the main function is to control the four mechanical devices. The mechanical device includes transmission source lifting device, detector lifting device, horizontal motion device and rotating plat device. All of the mechanical devices are equipped with limit switches for position detection. Every mechanical device has its own motion platform and driving module, which is used to drive the AC motor and control platform movement.
In this system, a photoelectric limiting switch is installed at the bottom of the device to determine the zero position. The lifting gear will move at a certain distance, based on each axis’ zero position as the datum mark. The speed of the motors is controlled by module EM253 and sends out varying pulse parameter values. Motor rotation generates pulses on the number one rotation using PLC programmed parameter values and are compared against the range of the motor leading screw that was rotated once. In order to guarantee the safety and reliability of the system while safeguarding the operating personnel, high precision inductive proximity switches are installed at opposite ends of the plats during operation. The switches realize the maximum and minimum protections of the movement direction. The ball screw nut and slide guide may then be directly connected to the servo motor shaft by coupling. As a result, it ensures a high precision in regard to transmission.

4 Testing and findings

4.1 System programming and results

In the waste drum detection control system, the SIEMENS S7-1200 PLC was used as the main controller, and the SIEMENS STEP7 software was adopted as the program plant. The main functions of the system include motion control of the horizontal transmission platform, motion control of the lift platform of the detector, motion control of the lifting platform, control of the beam splitter and motion control of the rotating platform. The system also possesses safety interlocks and fault alarms. The functional diagram is shown in figure 3.

The detection and control system of waste liquid drums consists of five parts: one main program and four subroutines. The four subroutines are the automatic system subroutines, horizontal motion subroutines, detector lifting subroutines and radiation source lifting subroutines, respectively.

The main programming flowchart is shown in figure 4a. The subprogram flow of position control flow chart is shown in figure 4b, and the system detector and source lifting flow chart is
Figure 3. The system function of control software diagram.

shown in figure 4d. The main automatic control process is divided into the detector and source synchronous lifting scanning process. The system’s automatic operation chart is shown in flow chart 4c. We may program the system according to the flowchart.

Its main control process is as follows:

1) The waste drum is hoisted to the predetermined rotating table, and the horizontal movement is determined to be in the right place. Then, the drum rotates according to its preset speed.

2) Both the detector and transmission source are lifted at the same height on both ends of the waste drum.

3) The transmission source block is opened in front of the beam splitter.

4) The radioactive waste drum is tested.

5) The transmission source and detector continue to rise until the measurement of the waste liquid drum section is completed.

6) The transmission source and detector return to their original positions, and the block beam splitter resets. The drum stops rotating, and the waste drum is removed from the test area.

During detection, the fault alarm procedures of the system detect various fault states. When a fault occurs, the buzzer will ring, and detection will stop immediately.

4.2 System control configuration design and monitoring results

The detection control system configuration interface was designed using SIEMENS TP270 touch-screen monitor. The configuration program was made by the WinCC flexible software. The computer compiled text files, action buttons, object graphics files and other dynamic displays
Figure 4. (a) The system main flow chart. (b) The horizontal movement control flow chart. (c) The system automatically operation flow chart. (d) The system detector and source lifting flow chart.
within the software. The touch screen interacts with the computer through a serial interface. We may download programs into the touch screen from the computer.

The configuration interface of the waste drum and control system were comprised of three parts: the control of the login screen, automatic control operation interface and fault alarm interface. Other monitoring interfaces encompass data querying for real-time locations and historical positions as well as emergency stop control interfaces.

The main detection interfaces is shown in figure 5a. The operation interfaces of control and detection system is shown in figure 5b, and position detection fault alarm of the system AC motor is shown in figure 5c

5 Conclusions

The present study puts forward a detection device for the automatic control and monitoring system of low-level nuclear waste drums. The device is composed of machinery equipment, automated systems, a programmable logic controller, electric installations for equipment protection, an HPGe detector and an external gamma-radiation transmission source. The system enables fully automatic measurements, realizes accurate control of mechanical motion and completes system logic, sequential control and scanning control. Control requirements for the horizontal motion, rotation and segmentation scanning processes of the nuclear waste drums are also achieved. This paper proposes a method to detect the nuclear waste drum. This paper does not give a specific inspection time, according to the different needs of nuclear waste different time, according to the experimental verification. The average detection accuracy is similar to that of the original system, so the energy spectrum of nuclide can be detected effectively.

SGS technology is used in the detection of nuclear waste drums and is mainly used in transmission and radiation. The measurement speed is rapid, but the accuracy is not reliable. Hence, this technique is only adopted in non-uniform and low-density measurements. However, its success lies in its improvements of the measurement speed following the use of automated controls. Moreover, it enhances the detection accuracy in the control of rotated waste drums at a constant speed. Simultaneously, the positions of the source and detector are resolute. We use the SIMATIC WinCC flexible software to complete the configuration design, which reflects real-time control via dynamic interface conditions. The software monitoring interface is perceptive and intuitive, and it improves safety while streamlining many aspects in end-user operation.

The proposed automatic control system has set forth the standards of nuclear waste drum detection. It improves the work efficiency of laboratory personnel while concurrently running detections, enabling additional samples to be detected simultaneously. With the inevitable improvement of automation, nuclear waste drum detection will become increasingly industrialized. This concept has already been applied within laboratory and field settings. Therefore, it has excellent practical considerations in its application.

6 System issues and future research

This study has encountered various challenges and deficits during the design process. Various problems continue to exist in the control. Consequently, appropriate improvements to the control method have been scheduled.
Figure 5. (a) Main detection interfaces of the system. (b) The operation interfaces of control and detection system. (c) Position detection fault alarm of the system AC motor.
The problems are as follows:

1) The system produced electromagnetic noise during the operation, which interferes with the detection of spectrometer.

2) The abnormal temperature spike during the horizontal drive motor operation relative to other motors will occur in a short period of system operation, causing the motor to stall, thus leading to the normal horizontal motion axis to fail.

3) The system displayed real-time operating data in the equipment, however, the device is unable to store the data prior to being restarted, causing inaccuracies in equipment control and real-time monitoring.

4) The system motor operation causes interference for the detector, hence, there are intermittent errors in the results.

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Conflicts of interest. We declare no financial and personal relationships with other people or organizations that can inappropriately influence this paper. There is no professional or other personal interest of any nature or kind in any product. We confirm that there is no conflict of interest regarding the publication of this paper.

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