Design and Implementation of the LHAASO-WCDA Ultrasonic Ranging System Postprint

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Abstract

For the water-based Cherenkov detector array ranging system of the Large High Altitude Air Shower Observatory, a ranging system based on ultrasonic ranging technology is proposed, and its hardware and software design is completed. The lower computer of the system, with LVCN318 and PLC as its core, is primarily responsible for data acquisition and processing; the upper computer part, based on OPC technology, realizes communication between the upper computer and PLC as well as data display and storage. Using this system, experiments on obstacle ranging and liquid level measurement were conducted respectively. Experimental research demonstrates that the errors of both liquid level measurement and obstacle distance measurement are less than 11 mm, which falls within the error range of LVCN318, thus laying a foundation for the design and development of the water-based Cherenkov detector array ranging system.

Full Text

Design and Implementation of the LHAASO-WCDA Ultrasonic Distance Measuring System

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Abstract: This paper presents the design and implementation of an ultrasonic distance measuring system for the Water Cherenkov Detector Array (WCDA) of the Large High Altitude Air Shower Observatory (LHAASO). The system' s slave computer, centered around the LVCN318 sensor and a Programmable Logic Controller (PLC), performs data acquisition and processing. The upper computer component, based on OPC technology, enables communication between the upper computer and PLC as well as data display and storage. Experiments on obstacle ranging and liquid level measurement demonstrate that both measurement errors remain below 11 mm, within the error tolerance of the LVCN318 sensor, thereby establishing a foundation for the design and development of the WCDA ranging system.

Keywords: ultrasonic; LVCN318; distance measurement; measuring error; OPC

The Water Cherenkov Detector Array (WCDA) of the Large High Altitude Air Shower Observatory (LHAASO) is deployed in water pools 4 meters deep to capture Cherenkov light produced by cosmic ray secondary particles in water. To ensure normal WCDA operation, the attenuation coefficient of the water medium must be monitored to guarantee it exceeds 20 m. Water attenuation coefficient measurement is directly related to water level, making the WCDA ranging system essential for pool level measurement and reliable detector array operation.

Ultrasonic ranging is a non-contact detection technology that offers broader applicability, lower environmental sensitivity, and easier integration or miniaturization compared to laser or infrared ranging methods. It has been widely applied in obstacle detection, liquid level measurement, and other fields. In recent years, domestic researchers have conducted various studies on ultrasonic ranging technology. Some have applied it to collision avoidance: Jiang Lingxiao implemented ranging for substation safety distance monitoring; Xu Jingbo et al. designed a tower crane anti-collision detector based on ultrasonic ranging; and Zhong Yuan et al. developed a reversing anti-collision warning device. Others have applied liquid level measurement to transportation, petrochemical industries, and other sectors: Wang Zhikun et al. designed a liquid level detector for yacht applications capable of precisely monitoring fuel, drinking water, and sewage reserves; Hong Jian et al. employed intelligent ultrasonic level switches for oil tank monitoring; and Dong Hui designed a high-precision liquid level measurement system for fruit juice filling tanks that improved filling efficiency and automation.

While references [3-6] and [6-9] respectively address obstacle ranging and liquid level measurement, like most previous ultrasonic ranging research, these studies approach the problem from a single perspective without combining both aspects, limiting their application scope. This paper proposes an ultrasonic ranging system for the LHAASO-WCDA application, employing an ultrasonic level sensor and Programmable Logic Controller (PLC) to investigate both obstacle ranging and liquid level measurement. By analyzing measurement errors from both experiments, we evaluate the measurement precision of the ultrasonic level sensor, contributing to the design and development of the WCDA ranging system.

1.1 Ranging Principle

When acoustic waves propagate from one medium to another, differences in acoustic impedance cause the wave propagation direction to change at the interface. When the acoustic impedance difference between two media is substantial, nearly all 声波 energy is reflected. Ultrasonic ranging typically employs the time-of-flight method. This study uses a combined transmitter-receiver ultrasonic sensor. The sensor emits ultrasonic waves into the medium and begins timing simultaneously. The waves propagate to the target object, reflect off its surface, and return along the same path. The sensor stops timing upon receiving the reflected wave. Based on the ultrasonic propagation velocity in the medium and the measured time, the distance between the probe surface and the target can be calculated, as illustrated in [Figure 1: see original paper].

Given the ultrasonic propagation velocity v in the medium and the time recorded by the sensor t, the distance d between the probe surface and the obstacle is:

$$d = \frac{vt}{2}$$

Liquid level measurement operates on the same principle. With ultrasonic propagation velocity v in air, time t from emission to reception of the echo reflected from the liquid surface, and distance H between the ultrasonic sensor probe surface and the container bottom, the liquid level h is:

$$h = H - \frac{vt}{2}$$

Therefore, when using an ultrasonic level sensor for obstacle distance measurement, the relationship between measured liquid level (h) and distance (d) is:

$$d = H - h$$

1.2 Ranging Characteristics

During propagation, ultrasonic waves are susceptible to various external factors that alter their velocity and direction. The fundamental physical characteristics affecting ultrasonic ranging performance include:

1) Temperature: Ambient temperature significantly influences ultrasonic propagation velocity. The relationship between sound velocity error and temperature is:

$$\frac{\Delta v}{\Delta T} \approx 0.607\,\mathrm{m/s \cdot {}^{\circ}C}$$

This indicates that a 1°C temperature change alters sound velocity by approximately 0.607 m/s, yielding a velocity error of up to 6.8% when ambient temperature varies between 0°C and 40°C. Ultrasonic ranging systems can incorporate temperature compensation modules to address velocity variations with temperature.

2) Frequency: Ultrasonic frequency affects beam width, which determines directional strength. Higher frequencies produce larger radiation areas, narrower beam widths, and stronger directionality, while lower frequencies yield smaller radiation areas, wider beam widths, and poorer directionality. Frequency also relates to measurement range and precision. During propagation, ultrasonic waves experience attenuation through diffusion, scattering, and absorption, with attenuation increasing with frequency. Consequently, measuring longer distances requires lower frequencies. However, frequencies cannot be too low, as excessively long wavelengths increase measurement error. Therefore, selecting an appropriate ultrasonic frequency based on range and precision requirements is critical. Additionally, hardware circuits can amplify echo signals according to measurement distance to maintain constant echo amplitude.

2.1 Overall System Design

The ultrasonic ranging sensor employs the OMEGA LVCN318, a multifunctional non-contact level sensor designed for liquid level measurement. The LVCN318 features automatic temperature compensation, adjustable measurement range, a 7.6 cm beam width, and ±11 mm precision. It provides robust handling of the two primary ranging characteristics mentioned above and is particularly suitable for measuring corrosive, viscous, or contaminated liquids. The system utilizes a PLC as the core component for signal acquisition, processing, and communication with the upper computer, offering strong adaptability and high stability in high-altitude, low-temperature environments. The upper computer employs a standard computer or industrial PC for ranging monitoring.

2.2 Hardware Design

[Figure 2: see original paper] illustrates the hardware composition of the ultrasonic ranging system. The LVCN318 emits and receives reflected ultrasonic signals, converting them into 4-20 mA level signals transmitted to the PLC analog input module (SM331). The SM331 primarily consists of A/D conversion components, analog switching circuits, compensation circuits, and optocouplers, converting the sensor’ s current signals into digital signals for internal PLC processing. The processed distance (or level) signals are transmitted via the Ethernet communication module (CP343-1) to an industrial computer for display and storage.

The system employs OPC (OLE for Process Control) technology to address communication between the industrial computer and PLC. OPC is a technical specification and industrial standard based on Microsoft’ s OLE/COM and

DCOM technologies, providing a unified interface specification for server-client connections. The OPC server is built upon Siemens' SIMATIC NET communication software. After establishing an OPC Server on the PC, data mapping can be created between the OPC Server and PLC via Ethernet. OPC Clients cannot directly access the OPC Server kernel but can interact through COM interfaces, as shown in [Figure 2: see original paper].

2.3 Software Design

The system software comprises PLC control software and monitoring software. The PLC control software acquires the 4-20 mA level signal from the ultrasonic level sensor, converting the current signal into actual level or distance values. Processed data is stored in process image or bit memory areas.

The monitoring software, acting as the OPC Client, is developed on the Visual Studio 2010 platform and primarily performs data acquisition, display, and storage, with the control flow shown in [Figure 5: see original paper]. The OPC Server consists of server objects, group objects, and item objects. The server object serves as a container for group objects, containing all server information. Group objects manage both their own information and OPC items. Items are objects within the OPC server that store tags required by OPC clients, representing logical connections to physical data sources rather than the sources themselves—each OPC server item corresponds to an address in the PLC. Since item objects provide no external interface, client programs cannot operate directly on data items but must manipulate them through group objects. This system employs a subscription-based data access method, where the server periodically scans data buffers and notifies clients to transmit data when changes exceed a certain threshold.

3 Ranging Results and Analysis

[Figure 3: see original paper] presents the monitoring software flowchart. For the obstacle ranging experiment, a paperboard served as the obstacle, moved by an electric translation stage with 0.00125 mm single-step resolution. Due to transmit pulse residual vibration interfering with echo detection, the sensor exhibits a blind zone of approximately 200 mm. Starting from 200 mm to avoid this zone, the obstacle was moved 10 mm per step, with 20 consecutive measurements taken at each position and averaged to obtain the measured value.

[Figure 4: see original paper] shows the obstacle ranging results at room temperature. Within the 200-700 mm range, measured distance exhibits a linear relationship with actual distance, approximating:

$$y = bx + a$$

Thus, the systematic error is constant. After correcting the systematic error by subtracting 9 mm, the measurement error becomes ±10 mm, with an average measurement error of -0.7 mm.

For the liquid level measurement experiment, water was added incrementally to a container under sensor installation requirements. At each level, manual measurements were taken as actual values, while the LVCN318' s average of 20 consecutive measurements served as the measured value. Results shown in [Figure 5: see original paper] demonstrate a linear relationship between actual and measured levels within the 30-300 mm range. After systematic error correction, level measurement errors remain below 10 mm, with an average error of 0.7 mm.

These results indicate that both obstacle distance and liquid level measurement errors fall within the same range and remain within the sensor' s measurement precision. The primary error source is the external environment. Potential error causes include:

1) **Obstacle Measurement:** Echoes reflected from surrounding objects affect results. The ultrasonic sensor emits divergent 声波 that may reflect first off the translation stage surface (experimental platform or walls) before reflecting off the target board and returning to the sensor, increasing the propagation distance and yielding larger measurements.

2) **Liquid Level Measurement:** During level measurement, some ultrasonic energy enters the water and reflects off the container bottom, producing echoes that yield smaller measurements. Manual level measurement also introduces significant error.

Additionally, the LVCN318 outputs a 4-20 mA level signal corresponding to a PLC decimal range of 0-27648, representing a level of 0-h. Quantization calculations within the PLC involving rounding also introduce certain errors.

4 Conclusion

This study constructed an ultrasonic ranging system using the LVCN318 ultrasonic level sensor combined with a PLC, achieving distance signal acquisition, processing, display, and storage. Obstacle ranging experiments within the 200-700 mm range demonstrated measurement errors of ±10 mm, while liquid level measurement experiments within the 30-300 mm range showed errors below 11 mm, both within the LVCN318' s allowable error range. The ranging results confirm that the LVCN318 is suitable for both solid and liquid target objects. Error analysis reveals that surrounding objects—i.e., sensor installation conditions—affect ranging accuracy. The design and implementation of this system establish a foundation for WCDA ranging system development, providing a basis for optimizing monitoring schemes, improving equipment selection, and refining installation environments in future work.

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Note: Figure translations are in progress. See original paper for figures.