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Innovative Application of Fiber Optic Transmission in Industrial Secondary Control and Instrument Signal Transmission

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Abstract: *With the continuous improvement of industrial automation level, traditional cables are difficult to meet the needs of industrial secondary control systems for high reliability and low latency signal transmission due to strong electromagnetic interference, short transmission distance, high bit error rate and other problems in signal transmission. To this end, this paper introduces fiber optic transmission technology and designs a long-distance and high-reliability signal transmission solution based on fiber optics for the key pain points in the transmission of status display signals of instrument landing systems (ILS) in industrial sites, especially airport towers. This solution collects control signals through a microcontroller, combines the optoelectronic conversion module with the link status monitoring mechanism, and realizes all-optical signal transmission while enhancing the system's anti-interference and fault self-recovery capabilities. Experiments show that at 10kHz, the error of the remote output waveform is 2.1%; when the frequency is increased to 50kHz, the error is 3.5%; even at a high frequency of 100kHz, the error is still controlled within 4.8%, which meets the system's set error tolerance standard of less than or equal to 5%. The system's transmission accuracy and linear response capability in multiple frequency bands fully demonstrate its feasibility and reliability in transmitting high-fidelity signals in industrial control environments.*

Keywords: *Optical Fiber Transmission; Industrial Secondary Control; Instrument Signal; Anti-Interference Design; Long-Distance Communication*

1. Introduction

With the continuous improvement of industrial automation and informatization, industrial control systems have put forward higher and higher requirements on the real-time, stability and anti-interference capability of signal transmission. Especially in key areas such as power, aviation, and rail transit, the secondary signal links that control systems rely on often need to achieve long-distance, highly reliable data transmission in strong electromagnetic interference, high-density equipment, and complex environments. However, traditional copper cable transmission methods are susceptible to interference, have large signal attenuation, high bit error rate, and limited transmission distance, making it difficult to meet the needs of modern industry for high-quality control communications.

Fiber optic communication technology has gradually become an important alternative for industrial signal transmission due to its physical advantages such as low loss, strong resistance to electromagnetic interference, large bandwidth, and long transmission distance. At present, optical fiber has been widely used in data centers, communication backbone networks and other fields, but its engineering practice in industrial secondary control and instrument signal transmission is still relatively limited, especially lacking in structured transmission solutions for key low-speed signals such as status display and control instructions in complex environments.

To this end, this paper proposes a long-distance transmission solution for industrial control signals based on optical fiber, combining optoelectronic conversion, link status detection and multi-channel control circuit design, while ensuring signal integrity and security, to improve the system's anti-interference ability and operation and maintenance efficiency. Through application verification in actual engineering environments, the solution has demonstrated good performance and promotion prospects, and has the potential for the integrated development of 5G-A and industrial Internet of

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Things in the future.

2. Related Works

With the rapid development of optical fiber communication technology, research on dispersion effects, amplification technology, modulation methods and new sensing and communication solutions in signal transmission has continued to deepen. This paper can review the key technological progress and innovative applications in related fields in recent years.

Islomov introduced the calculation method of signal dispersion in optical fiber. Chromatic dispersion refers to the phenomenon that the time or mode components of the signal are extended and the pulse width increases at the receiving end due to the different propagation speeds of different frequency components during the transmission of optical pulses. Chromatic dispersion limits the signal transmission quality in optical fiber communication and is a key issue that needs to be addressed in optical fiber communication technology [1]. Ramkumar et al. studied the management of total loss and dispersion effects in ultra-high-speed optical transmission based on hybrid amplification systems and the improvement of optical fiber transmission distance. By weighing the optical components, fiber types and amplification technologies, a variety of hybrid amplification schemes and spatial division multiplexing technologies were used to effectively enhance the signal strength [2]. Xie et al. proposed a single-carrier and orthogonal frequency division multiplexing hybrid coherent optical transmission scheme based on 1-bit bandpass Δ-Σ modulation. This scheme uses I/Q (In-phase/Quadrature) modulator to realize high-order 512QAM (Quadrature Amplitude Modulation) signal transmission, effectively suppressing quantization noise and reducing the complexity of digital signal processing [3]. Liyakat K S S and Liyakat K K S introduced the impact of dispersion in optical fiber on signal quality and its compensation method. In optical fiber transmission, dispersion can cause optical pulse broadening and affect the signal-to-noise ratio [4]. Fan et al. proposed a Distributed Fiber Acoustic Sensing (DAS) system based on multi-segment relay amplification, using a bidirectional erbium-doped fiber amplifier to simultaneously amplify the detection light and the backscattered light, in order to break through the limitations of φ-OTDR (Phase-sensitive Optical Time-Domain Reflectometry) in long-distance measurement. By optimizing parameters, the system can theoretically achieve signal detection over 2,500 kilometers [5]. Li et al. proposed a differential cantilever-enhanced fiber photoacoustic sensor to suppress external vibration and noise interference and achieve gas diffusion detection. The sensor consists of two symmetrical photoacoustic cavities and a pair of differential interference cantilevers, and the signal is recovered by white light interferometric demodulation. Experiments show that this structure can improve environmental noise suppression by 80%[6]. Luo et al. used adaptive discrete multi-tone and QAM modulation to improve spectral efficiency, and introduced a sparse structure reserve calculation algorithm for receiving end equalization processing. The experiment achieved a transmission rate of 113.175 Gbps, setting a record in the field of visible light laser communications and demonstrating its application potential in data center interconnection and high-speed indoor access[7]. Jihad and Almuhsan studied the effect of the switching voltage of the Mach-Zehnder modulator on the performance of the millimeter-wave wireless optical fiber system, using the SCM-ASK (Subcarrier Modulation - Amplitude Shift Keying) modulation method and analyzing the signal quality through eye diagrams. The results showed that about 10V is the optimal switching voltage, which can significantly improve the quality of the received signal [8]. Gao et al. proposed a new design method, which reduces the diameter of the microstructure by 16% while maintaining excellent optical performance by cutting the outer tubular structure of the multi-layer anti-resonant hollow-core optical fiber by 130°. The loss of the experimentally prepared optical fiber in the O-band and C-band is as low as 0.28 dB/km and 0.23 dB/km respectively[9]. Lan et al. realized bendable and responsive crystal materials through molecular design and crystal engineering, and self-assembled with inorganic/polymer to form multifunctional composite materials, which are widely used in sensors, soft robots and optoelectronic devices[10]. Shi et al. designed an attention-based heterogeneous neural network ATTH (Attention-based Heterogeneous Neural Network) modeling communication link, and experimentally achieved a rate of 80.78 Gbps in a 5 km optical fiber + 1 m terahertz link at a frequency of 209 GHz, with a bit error rate lower than the SD-FEC (Soft-Decision Forward Error Correction) threshold. This method improves the receiving sensitivity and has the potential to achieve 6G high-speed and low-cost communication [11]. Existing research still faces bottlenecks such as high system complexity, insufficient anti-interference ability, and difficulty in coordinated transmission of multiple types of signals when achieving long-distance high-quality optical fiber signal transmission.

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3. Methods

3.1 Optimization Path for Signal Transmission Quality

With the continuous advancement of industrial automation and informatization, the control system's requirements for signal transmission quality are also continuously increasing. Especially in scenarios such as redundant control, state interlocking, and remote monitoring, the real-time, reliability, and anti-interference capabilities of signal transmission have become core indicators for measuring system stability. Although the traditional copper cable transmission method has certain advantages in terms of cost and layout, it is susceptible to external electromagnetic interference and radio frequency interference due to its significant resistance and capacitance characteristics, resulting in serious signal attenuation and waveform distortion during long-distance transmission, which ultimately affects the accuracy and safety of control logic execution.

Especially in key places with extremely complex electromagnetic environments, such as airport towers, radar stations, substations and rail transit control centers, signal integrity is directly related to the real-time feedback of equipment operation and the accuracy of operator command execution. Once the signal is interfered or the transmission fails, it is very easy to cause control misjudgment, status display delay and even major safety accidents. Therefore, building a transmission channel with high anti-interference ability, low bit error rate and stable synchronization characteristics is a core problem that needs to be solved in the current industrial secondary control system.

To this end, this paper proposes a long-distance control signal transmission solution based on optical fiber communication technology. Optical fiber communication uses high-purity glass or polymer as the transmission medium, and realizes the long-distance, high-fidelity transmission of optical signals in the optical fiber through the principle of total internal reflection, which is almost free from external electromagnetic interference. Compared with traditional cables, optical fiber transmission loss is extremely low, and the signal strength can be kept stable over a distance of several kilometers, avoiding signal amplitude attenuation and waveform distortion, greatly improving signal quality and system operation reliability.

In addition, the high bandwidth characteristics of optical fiber also give it a significant advantage in high-data-volume, high-resolution signal transmission. In the transmission of high-definition and ultra-high-definition video signals, traditional copper cables are prone to frame loss and image quality compression due to limited bandwidth. Optical fiber can easily support lossless transmission of 4K, 8K and higher bit rate signals, ensuring that the data is not compressed or disturbed. It is suitable for complex application scenarios such as high-definition monitoring and feedback, AI image analysis, and edge processing in industrial sites. At the same time, the natural electrical isolation characteristics of optical fiber also provide additional safety protection for the control system, avoiding voltage interference caused by ground loops, lightning strikes or equipment short circuits, greatly enhancing the protection and stability of the system.

3.2 Systematic Integrated Design of Hardware Circuits

In order to meet the long-distance and high-stability transmission requirements of multi-channel state quantities and control signals in industrial secondary control systems, this paper designs a systematic hardware circuit architecture for optical fiber transmission. The core modules include three parts: video buffer circuit, signal conversion circuit and control circuit. The three parts work together to form a closed-loop logic of signal acquisition-transmission-reduction.

(1) Video buffer circuit

The buffer circuit is mainly used to improve the driving ability of the source signal and the anti-interference ability of the receiving signal. In this scheme, for the analog signal output by the cable TV or industrial video monitoring source, the operational amplifier parameters are first adjusted, and a dedicated video driver unit is designed to improve the signal front-end quality. Buffer modules are set at the transmitting and receiving ends to prevent waveform instability caused by signal echo or load fluctuation, thereby ensuring the clarity and stability of the signal during long-distance transmission.

(2) Signal conversion circuit

This module is the key hub of the entire circuit system. It is responsible for completing the high-precision bidirectional conversion between analog signals and digital signals, and modulating the

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signals into a format suitable for optical transmission. Multiplexing and demultiplexing units are set up in the system to realize the parallel transmission of multiple signals in a single optical fiber. The multiplexing unit organizes and encodes the multiple signals according to the channel timing and enters the optical transmitter; the demultiplexing unit parses them into independent channels at the receiving end. By controlling its logical scheduling through FPGA (Field-Programmable Gate Array) or embedded MCU (Micro controller Unit), crosstalk between channels or timing desynchronization can be effectively prevented, ensuring efficient coordination of various control signals.

(3) Control circuit design

The control circuit is responsible for regulating the overall system timing, including the whole process scheduling of the transmitter trigger, light emission synchronization, receiver restoration timing, and indication output response. The system design uses a programmable clock controller and a multi-stage phase-locked loop to generate a synchronous timing signal, and cooperates with the double-end timing control logic to ensure synchronous transmission of data frames and conflict-free demultiplexing. In addition, the status indication output part is connected to the status display light board or industrial HMI (Human-Machine Interface) terminal through the driving logic to achieve real-time status feedback.

3.3 Technical Implementation of Fiber Optic Transmission Solution

The system uses a high-performance microcontroller as the control core, and collects external switch quantities or analog signals through GPIO (General-Purpose Input/Output) or ADC (Analog-to-Digital Converter). After encoding and modulation, the collected signal is converted into an optical signal through an optical transmitter and transmitted to the remote end along a single multi-mode or single-mode optical fiber. At the receiving end, the optical receiver restores the signal to an electrical signal, which is decoded and buffered by the controller and then output to the status display board or control actuator.

This solution supports parallel multiplexing of multiple signals. One optical fiber can transmit dozens of switch control signals at the same time, with a transmission distance of more than 5 kilometers, and does not rely on relay amplifiers, which greatly reduces the complexity of engineering wiring and the overall cost of the system.

In terms of anti-interference, the system introduces multiple protection mechanisms: first, the optical fiber medium itself has a strong ability to resist electromagnetic interference; second, the system introduces differential input design and filtering network to effectively suppress access-end interference; third, through the link status detection mechanism (Link Status Detection), when the link is interrupted, the module loses power or the bit error rate is too high, the system automatically switches to the "fail-safe" state (all indicators are off) to avoid misleading operators due to erroneous displays. At the same time, the mechanism also has a recovery detection function, which can automatically identify and restore the display when the link is reconnected.

Through the above architecture and design, this solution shows good transmission performance and system stability in practical applications, and is particularly suitable for industrial application scenarios with extremely high requirements for safety and reliability, such as airport tower signal synchronization, power system status indication, and rail transit train control information display.

4. Results and Discussion

4.1 Experimental Environment and Test System

Experimental location

Laboratory test: simulated industrial signal control system, adjustable length optical fiber link;

Engineering site test: Shanghai Hongqiao Airport ILS renovation project.

Test equipment

Microcontroller acquisition module ×2

Photoelectric conversion module (850nm/1310nm) ×2

Single-mode optical fiber jumper (up to 5km)

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EMC interference source (simulated radar, motor start, electric welding and other high-frequency interference)

Oscilloscope, bit error meter, delay analyzer, etc.

4.2 Data Statistics and Result Recording

The experiment used three repeated measurements and took the average value to ensure data stability and repeatability. By comparing the bit error rate, response time and fault handling efficiency of the traditional copper cable solution and this optical fiber solution under the same environment, the performance improvement was further quantified.

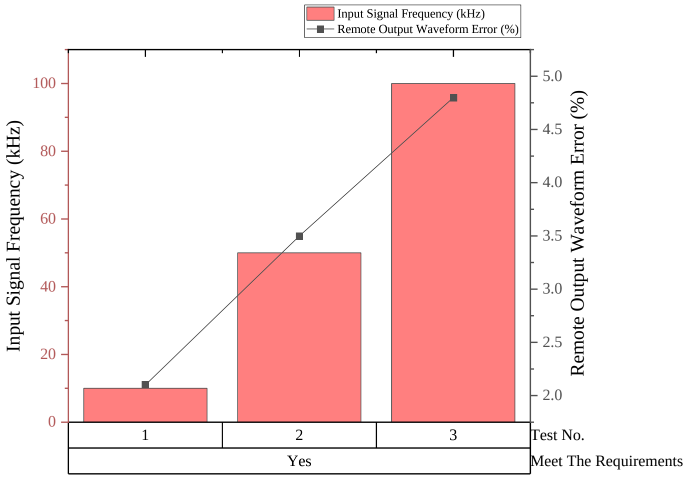

Figure 1 Signal integrity

In the signal integrity test, the system inputs standard TTL pulse signals with frequencies of 10kHz, 50kHz, and 100kHz, respectively, transmits them to the remote receiving end through optical fiber, and uses an oscilloscope to measure the error percentage between the restored waveform and the original waveform. The experimental data shows that at 10kHz, the error of the remote output waveform is 2.1%. When the frequency is increased to 50kHz, the error is 3.5%; even at a high frequency of 100kHz, the error is still controlled within 4.8%, which meets the system-set error tolerance standard of less than or equal to 5%. The test results in Figure 1 show that the optical fiber transmission system can stably maintain signal integrity at different input frequencies without obvious waveform distortion or signal loss. This verifies the system's transmission accuracy and linear response capabilities in multiple frequency bands, fully demonstrating its feasibility and reliability in transmitting high-fidelity signals in industrial control environments.

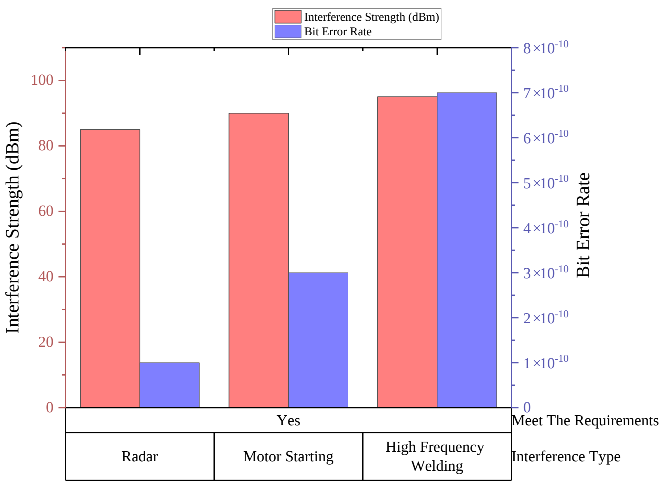

Figure 2 Anti-interference capability

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In the anti-interference capability test, the experiment selected three common interference sources in typical industrial sites: radar signals, motor startup shock, and high-frequency welding arc interference, and tested the bit error rate of system signal transmission at interference intensities of 85dBm, 90dBm, and 95dBm respectively. The results show that under radar interference conditions, the system bit error rate is only 1×10^{-10}; under motor start-up interference environment, the bit error rate is 3×10^{-10}; even under high-frequency welding conditions with the highest interference intensity, the bit error rate only rises to 7×10^{-10}, which is still significantly better than the traditional cable system used in similar interference environments, with a typical bit error level of 10^{-7} to 10^{-6}.

The test results in Figure 2 show that the optical fiber transmission solution has strong anti-interference ability when facing strong electromagnetic interference, which can effectively avoid signal distortion or control failure caused by interference, and has engineering applicability for stable operation in complex electromagnetic environments such as airports, substations, and rail transit.

In the long-distance transmission capability test, the fiber link lengths were set to 1km, 2.5km, 5km, and 6km, respectively, to test the system's bit error rate performance under different distance conditions and whether relay amplification was required. The experimental results show that within a range of 1km, the system bit error rate is 0, and the signal quality remains optimal. When the transmission distance is extended to 2.5km and 5km, the bit error rates are 1×10^{-10} and 2×10^{-10}, respectively, which are still at an extremely low level, and high-quality transmission can be achieved without relay amplification, which fully meets the system design indicators (as shown in Table 1).

Table 1 Long-distance transmission

Test No.	Transmission Distance (km)	Bit Error Rate	Is Relay Amplification Required?	Meet The Requirements
1	1	0	No	Yes
2	2.5	1×10^{-10}	No	Yes
3	5	2×10^{-10}	No	Yes
4	6	5×10^{-7}	Yes	No

However, when the transmission distance is further extended to 6 km, the bit error rate rises sharply to 5×10^{-7}, the system stability decreases significantly, and it is necessary to rely on relay amplification equipment to maintain basic transmission quality. At this time, it no longer meets the performance standards set by the system.

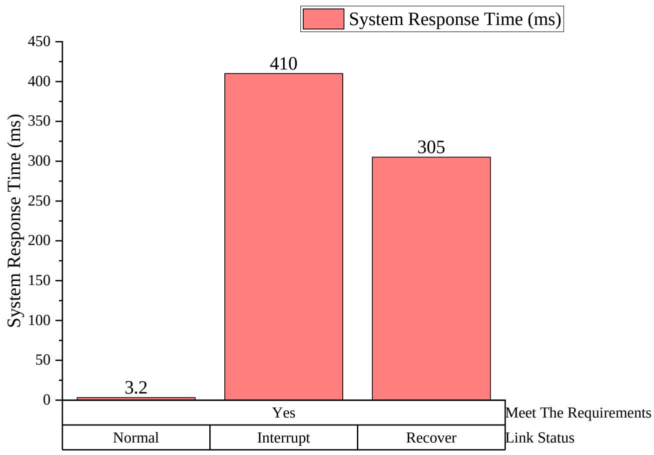

Figure 3 Response delay

In the response delay and fault handling mechanism test, the link is set in three typical states: "normal", "interrupted" and "recovered", and the system's response time to state changes is tested. The results show that when the link is working properly, the system response time is 3.2ms, which is far lower than the standard threshold of 5ms for industrial real-time communication, and has good real-time response capabilities. When the link is interrupted, the system can identify the link break within 410ms through the link status detection mechanism and trigger the "fail-safe" strategy, so that the status display panel automatically turns off all indicators to avoid misleading the operator, as shown in Figure 3. After the link is restored, the system can automatically identify the recovery status and relight the corresponding display indication within 305ms. The overall response logic is clear and the

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execution speed is stable and reliable. From the data results, it can be seen that the optical fiber transmission system has strong link status self-detection and adaptive response capabilities, and can realize rapid identification and emergency handling of abnormal conditions in complex industrial sites. This effectively reduces the risk of misoperation caused by link failure and improves the safety robustness and engineering credibility of the control system.

5. Conclusions

Focusing on the high reliability requirements of industrial secondary control and instrument signal transmission, this paper proposes and implements a long-distance control signal transmission solution based on optical fiber communication technology. By integrating microcontrollers, photoelectric conversion modules, link status detection mechanisms and multi-channel control circuits in the system, the traditional copper cable transmission effectively solves the problems of high bit error rate, short transmission distance and weak anti-interference ability in complex electromagnetic environments. The experimental test results show that the solution performs well in signal integrity, anti-interference, long-distance stable transmission and fault response capability. In particular, it can achieve 5km stable transmission without relays in actual engineering applications, significantly improving the operational reliability and maintenance efficiency of the control system. Although this study has verified the application advantages of optical fiber technology in the field of industrial signal transmission, the current system is still mainly oriented to the synchronous control of switching signals, and the transmission capacity of analog or high-frequency dynamic signals has not been deeply explored. Future work can further expand the application research of this solution in the coordinated transmission of multiple types of signals, intelligent scheduling management, and integration with edge computing and IoT devices to improve the intelligence level and technical adaptability of the system.

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