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(Review Article)

Integrating HMI display module into passive IoT optical fiber sensor network for water level monitoring and feature extraction

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Abstract

This research explores the integration of Human-Machine Interface (HMI) display modules with passive IoT optical fiber sensor networks to enhance water level monitoring systems. Utilizing Fiber Bragg Grating (FBG) sensors for their high sensitivity and reliability, this study aims to provide real-time data visualization and advanced feature extraction to aid in environmental management and flood prevention. The methodology involves deploying FBG sensors across water bodies, capturing data through an IoT gateway, and using HMI modules for user-friendly interfaces. Signal conditioning, feature extraction, and machine learning algorithms are employed to ensure data accuracy and predictive analytics. Testing and validation are conducted to ensure system robustness, with performance metrics including accuracy, reliability, response time, data integrity, and power efficiency. The integration of HMI display modules into optical fiber sensor networks presents a comprehensive solution for efficient and effective water level monitoring, improving data accessibility and decision-making capabilities.

Keywords: Water Level Monitoring; Optical Fiber Sensor Network; Human-Machine Interface (HMI); IoT Gateway; Feature Extraction; Data Integrity; Fiber Bragg Grating (FBG); MQTT

1. Introduction

In contemporary control systems, a Human-Machine Interface (HMI) display module is essential for managing, controlling, and monitoring complex systems through interactive interfaces. In water level monitoring, HMIs enhance data usability by providing real-time visualization, control options, and analytics. Key software components include real-time operating systems, embedded software, data processing and storage systems, communication protocols, and GUI development tools. Initially developed in the 1960s and 1970s alongside programmable logic controllers (PLCs), HMIs evolved significantly with advancements in graphics and microprocessor technologies in the 1980s and 1990s. Pioneering companies like Siemens and Honeywell have been instrumental in this field. Modern HMIs offer real-time monitoring, control interfaces, data visualization, alarm management, historical data analysis, and user-friendly interaction, making them invaluable across various domains.

Optical fiber sensor networks monitor water levels and other physical parameters with high precision by leveraging light transmission properties. Integrated into IoT frameworks, these sensors offer reliable, continuous monitoring and feature extraction, crucial for environmental management and flood prevention. The software components include data acquisition, signal processing, feature extraction techniques, communication protocols, data visualization tools, database management systems, and IoT platforms. Invented in the 1960s by Drs. Charles K. Kao and George Hockham, optical fiber technology saw practical applications in the 1970s and 1980s, with the development of advanced Fiber Bragg Grating (FBG) sensors in the 1990s. These networks aim to provide accurate water level measurements, real-time

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monitoring, scalability, durability, feature extraction, and enhanced decision-making, transforming water resource management and disaster preparedness.

Water level monitoring is vital for environmental management, infrastructure maintenance, and flood prevention. Traditional methods, often involving manual measurements or electronic sensors, can be costly, require regular maintenance, and are vulnerable to harsh conditions. The advent of IoT technologies has revolutionized environmental monitoring, offering robust, scalable, and cost-effective solutions. Optical fiber sensors, with their immunity to electromagnetic interference, high sensitivity, and durability in harsh environments, have become promising in this domain. Integrating HMI display modules into passive IoT optical fiber sensor networks enhances the usability and accessibility of real-time data, providing a user-friendly platform for monitoring and analyzing water levels.

Objectives

The primary objectives of this research are to design and implement an HMI display module that seamlessly integrates with a passive IoT optical fiber sensor network for water level monitoring, enabling real-time monitoring and user-friendly data visualization to facilitate immediate decision-making and response. Additionally, the research aims to develop and integrate feature extraction algorithms to analyze water level data for trends, anomalies, and predictive insights, and to validate the performance, reliability, and accuracy of the integrated system in various environmental conditions.

1.1. Research Gap

While optical fiber sensors and IoT technologies have been individually explored for water level monitoring, a significant gap exists in their integration with HMI display modules. Previous studies have primarily focused on sensor technology or IoT frameworks, with limited attention to user interfaces. This gap presents an opportunity to enhance the practicality and user engagement of water monitoring systems by incorporating an HMI display module that provides intuitive, real-time data interaction.

1.2. Problem Statement

Despite advancements in sensor technology and IoT, current water level monitoring systems often lack a comprehensive, integrated solution that combines robust sensor data acquisition with user-friendly interfaces. The absence of an HMI display module limits data accessibility and usability, hindering effective monitoring and timely decision-making. This research aims to address this issue by developing a holistic system that integrates a passive IoT optical fiber sensor network with an HMI display module, enhancing both functionality and user experience in water level monitoring systems.

By bridging the gap between advanced sensor technology and practical user interfaces, this research aims to develop a state-of-the-art water level monitoring system. Integrating HMI display modules with passive IoT optical fiber sensor networks will improve data accessibility and visualization, contributing to more efficient and effective water management practices.

2. Literature survey

The SMAT fibre laser, which boasts great precision and efficiency across a range of production processes, is an advanced technology proposed by Ding et al. (2017) for industrial applications. By maximizing energy efficiency and decreasing manufacturing time, this state-of-the-art laser technology ensures extraordinarily high-quality results. With its capacity to be reliable and durable, the SMAT fiber laser is a versatile tool that performs well in activities like cutting, welding, marking, and engraving. Long-term value for companies looking for improved industrial solutions is provided by its cost-effectiveness in spite of its creative characteristics.

Khan et al. (2018) provide a thorough system that makes use of smart sensors and Internet of Things technology to remotely monitor and manage microgrids. This system uses a smart sensor network to collect performance data in real time and makes use of the Internet of Things (IoT) for communication and control, making it easier to monitor and manage microgrid operations remotely. In doing so, it improves microgrid operations' resilience, efficiency, and dependability, allowing for proactive maintenance and optimal energy distribution. As a result, this strategy has the potential to significantly reduce costs and enhance the sustainability of energy management techniques.

By employing a TENG-based direct sensory transmission (TDST) mechanism, Wen et al. (2020) present a battery-free, short-range self-powered wireless sensor network (SS-WSN) that essentially does away with the need for traditional power sources. This invention decreases environmental effect while simultaneously reducing maintenance requirements. The technology is perfect for applications that require localized data transmission because it is specifically made for close-proximity communication. It produces power from ambient sources by utilizing energy harvesting mechanisms such as TENG, which guarantees continuous functioning. It makes effective data collecting and analysis possible by permitting seamless connectivity between various sensors. Additionally, it uses direct sensory transmission, which improves data transfer reliability and efficiency inside the network.

In order to monitor the water levels in spent fuel pools at nuclear power plants, Lee et al. (2020) suggest a Long-reach DWDM-passive optical fiber sensor network. By utilizing DWDM (Dense Wavelength Division Multiplexing) technology, this novel approach makes long-distance monitoring possible. The system uses passive optical fiber sensors to provide accurate and dependable data, solving important safety issues related to the water levels in spent fuel pools. Moreover, the network enables real-time data transmission, improving operating efficiency and safety protocols. It is noteworthy because it provides a reliable and affordable means of ongoing monitoring, which greatly enhances nuclear power plant safety and management in general.

The IoT gadget RiverCore, proposed by Moreno et al., (2019) is designed to use cellular connection technologies to monitor river water levels. Using cellular communication to ensure smooth data transmission, RiverCore is a monitoring instrument made especially for measuring river water levels.

In order to monitor and map floods, Arshad et al. (2019) suggest doing a systematic review that explores the integration of computer vision and Internet of Things-based sensors. Their main goal is to improve flood mapping, response, and detection systems by utilizing computer vision and Internet of Things sensors. They also investigate how AI-powered technologies might help with real-time flood control. They emphasize the opportunities and difficulties of using these technologies to increase flood resilience throughout their study.

An extensive evaluation of multiplexed passive optical fiber sensor networks designed for water level monitoring applications is proposed by Lee et al. (2020) Reviewing the workings of passive optical fiber sensor networks, the usefulness of these networks for water level monitoring is examined. It looks in-depth at the different multiplexing strategies used in these networks to improve data collection efficiency. In addition, the study presents prospects for enhanced water management and environmental monitoring and examines the most recent developments and unresolved issues in the sector.

According to Domingo (2012), the Internet of Things (IoT) offers a great chance to improve the lives of individuals with disabilities by providing creative solutions for inclusion, independence, and accessibility. People with disabilities can have access to a range of accessible features through Internet of Things devices, such as braille displays, voice-activated smart home appliances, and wearable technology, which encourages more inclusion and autonomy. People with impairments are also encouraged to be independent and mobile via smart navigation systems, remote monitoring tools, and adaptive transportation options made possible by Internet of Things technology. IoT also makes it easier to manage medications, access telemedicine services, and remotely monitor health issues, all of which contribute to universal healthcare. Those with speech or hearing impairments can communicate more easily thanks to IoT-powered communication devices, such as text-to-speech and speech-to-text apps. Furthermore, persons with physical limitations benefit from increased mobility and functionality thanks to IoT-driven assistive technologies like robotic aids, exoskeletons, and smart prostheses. In conclusion, the Internet of Things (IoT) has significant potential to enhance the standard of living and promote greater inclusion for people with disabilities by utilizing cutting-edge technical solutions.

Zhu et al. offer a thorough analysis of the development of Triboelectric Nanogenerator (TENG) technology, covering its innovative uses in nanoenergy and nanosystems as well as its beginnings in energy harvesting. The paper describes the evolution of TENG technology in detail, explaining how it is essential for converting mechanical energy into electrical energy for various uses. By means of an extensive analysis, it highlights the ways in which TENG has stimulated the development of nanoenergy, enabling energy production and application at the nanoscale and consequently opening up new opportunities in nanotechnology. Furthermore, the incorporation of TENG into nanosystems is outlined as a fundamental component that promotes the development of innovative gadgets and technologies. Underscoring the revolutionary possibilities of TENG developments, the paper explores their possible effects in a variety of fields, including electronics, healthcare, and environmental monitoring, heralding a new era of innovation and sustainability.

Chen and Zhou (2010)put out a unique strategy for remote structure health monitoring with RFID technology in an effort to improve heavy lifting appliance efficiency and safety. This device reduces the need for manual inspections by enabling real-time structural integrity monitoring from a distance. It also provides quick feedback and can identify potential faults early. It can be used in a variety of industries, including manufacturing, logistics, and construction. By seeing issues early on and taking action, it reduces maintenance expenses and downtime.

A comprehensive examination of the Internet of Things (IoT) within the realm of electric power and energy systems is suggested by Bedi et al., (2018) who also highlight the advantages, disadvantages, and potential uses of this technology. The integration of IoT technology is currently transforming these systems, enabling real-time monitoring, control, and optimization of energy generation, distribution, and consumption. Through IoT devices, there is a facilitation of preemptive maintenance and efficient allocation of resources by allowing remote monitoring of power grid infrastructure, equipment conditions, and energy consumption patterns. The utilization of IoT data analytics by power utilities could result in enhanced energy production optimization, decreased losses, and reinforced grid resilience, consequently boosting the overall efficiency and reliability of the energy system. Moreover, IoT facilitates the seamless integration of renewable energy sources like solar and wind power into the grid, thereby improving the management and coordination of decentralized energy production. Notwithstanding its potential benefits, the incorporation of IoT in energy systems encounters obstacles such as cybersecurity risks, interoperability challenges, and data privacy issues. These challenges highlight the necessity for sturdy regulatory frameworks and cybersecurity protocols. By focusing on edge computing, artificial intelligence, and advanced analytics, the research delves deeper into recent progressions and potential pathways for the implementation of Internet of Things applications in relation to energy and power systems.

Hsieh et al.'s (2012) study suggests combining 3G mobile networks and Programmable Logic Controllers (PLCs) with the Internet of Things (IoT) architecture to improve control, communication, and connectivity in IoT applications. It talks about how this integration might enhance control and data sharing capabilities by using 3G networks to give PLCs dependable, fast connectivity that allows real-time data transmission. IoT systems and devices may be remotely monitored and controlled thanks to integrated PLCs and 3G networks, which are scalable and adaptable to various IoT environments and applications. The security issues raised by this integration are also covered in the paper.

3. Methodology

Water level monitoring is essential for various applications, including flood management, reservoir management, and environmental monitoring. Traditional methods often involve manual measurement techniques, which are not only labor-intensive but also prone to inaccuracies. With the advent of IoT and optical fiber sensing technologies, automated water level monitoring systems have become more feasible, providing high accuracy and real-time data. Integrating an HMI display module into these systems can further enhance usability by offering immediate visual feedback and control options for operators.

3.1. System Design

3.1.1. Optical Fiber Sensor Network

Fiber Bragg Grating (FBG) sensors are chosen for their high sensitivity and reliability in measuring water levels. These sensors operate by reflecting specific wavelengths of light that shift with changes in strain and temperature, providing precise measurements. Sensors are strategically deployed across the water body or reservoir. Site surveys are conducted to identify optimal locations ensuring comprehensive coverage. Redundant sensors are placed at critical points to ensure continuous monitoring in case of sensor failure. Optical fiber sensors are connected to a data acquisition unit, capturing light signals and converting them into digital data. This data represents changes in water level detected by the sensors.

3.1.2. IoT Gateway

The IoT gateway acts as the central hub for collecting sensor data. It requires a microcontroller or microprocessor with sufficient processing power, communication modules for wireless data transmission, and power supply solutions for continuous operation. Embedded software is needed for data acquisition, preprocessing, and initial analysis. Communication protocols like MQTT or HTTP ensure efficient and secure data transmission. Data storage solutions are also required for buffering and local data logging.

3.1.3. HMI Display Module

The HMI display module includes a touchscreen display compatible with the microcontroller. It should have adequate resolution and processing power to handle the graphical user interface and real-time data updates. HMI development tools such as MyOpenLab or Node-RED Dashboard are used to create the user interface. Applications are tailored for real-time data visualization, system alerts, and historical data analysis.

3.2. Hardware Integration

Appropriate interfacing modules like Analog-to-Digital Converters (ADCs) or multiplexers are used to connect sensors to the IoT gateway. Secure and reliable connections are essential to prevent signal loss or interference. Serial communication methods like UART or SPI are used for direct connections between the IoT gateway and HMI display. Wireless options such as Wi-Fi or Bluetooth allow for remote placement of the display, offering flexibility in installation.

3.3. Software Development

Signal conditioning algorithms are implemented to filter noise and enhance sensor data accuracy. Calibration routines are developed to ensure sensors provide accurate readings by comparing outputs with known water levels. Lightweight communication protocols like MQTT are used for efficient data transfer. Data integrity and security are ensured using encryption and authentication mechanisms.

3.4. HMI Application Development

User interfaces are designed to be intuitive, incorporating visual elements like charts and graphs for real-time monitoring. Features for alert notifications and historical data analysis are implemented to enhance usability.

3.5. Data Communication Protocols

MQTT is chosen for its lightweight nature, operating on a publish/subscribe model for efficient data transfer. HTTP/HTTPS can be used for secure web-based communication. Error-checking mechanisms like checksums or CRCs are implemented to ensure data integrity. Data buffering techniques handle intermittent connectivity issues, preventing data loss during transmission.

3.6. Sensor Deployment and Calibration

Site surveys are conducted to determine optimal sensor locations, considering factors like water flow paths and accessibility. Redundant sensors are placed at critical points to ensure continuous monitoring. Known water level references are used to calibrate sensors, adjusting outputs accordingly. Regular recalibration accounts for environmental changes and sensor drift, ensuring long-term accuracy.

3.7. Feature Extraction Techniques

Filters like Kalman filters or low-pass filters smooth data and remove noise. Signal processing techniques identify and remove outliers, ensuring data reliability. Key features like water level trends and peak levels are identified, providing insights into water dynamics. Statistical methods analyze data, calculating metrics like mean and variance.

3.8. Advanced Techniques

Machine learning algorithms like neural networks or SVMs offer advanced pattern recognition and anomaly detection. Time-series analysis allows for predictive modeling based on historical data.

3.9. Testing and Validation

3.9.1. System Testing

End-to-end testing ensures all components work together seamlessly. Testing under various conditions ensures system robustness and reliability.

3.9.2. Validation

Comparing system output with manual measurements validates accuracy. Benchmark datasets validate machine learning models, ensuring reliable predictions.

4. Architectural diagram of Real-Time Water Level Monitoring and Feature Extraction System

This architectural diagram provides a visual representation of how the various components of the system interact to facilitate water level monitoring and feature extraction.

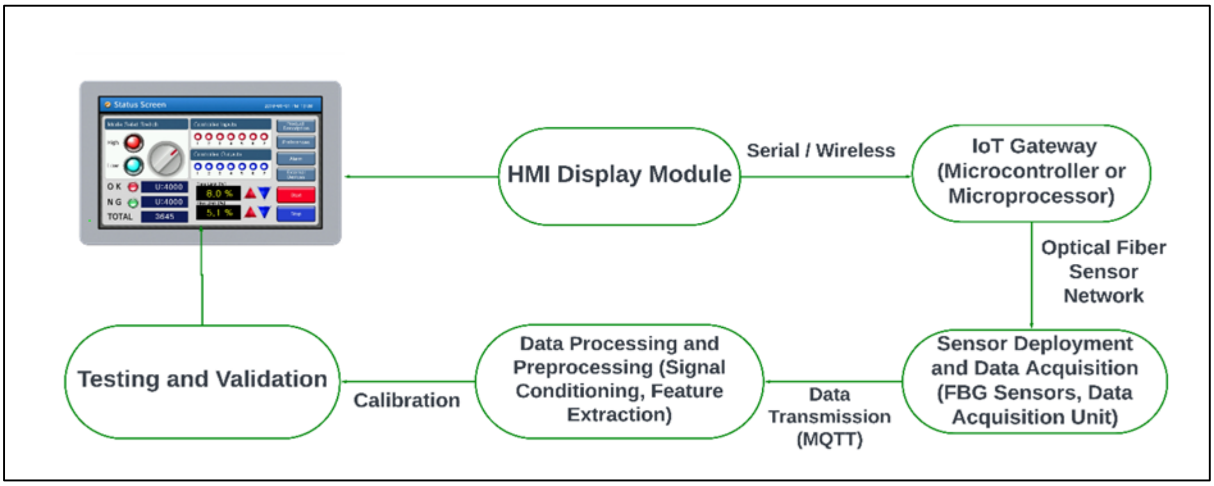

Figure 1 Integrated Architecture for Real-Time Water Level Monitoring and Feature Extraction System

This architectural diagram illustrates the flow of data and control between different components of the system:

- ***HMI Display Module:*** This module provides the user interface for real-time data visualization and system control. It communicates with the IoT gateway for data exchange.
- ***IoT Gateway:*** The central hub for collecting sensor data, preprocessing it, and transmitting it to the HMI display module. It also manages communication with the optical fiber sensor network.
- ***Sensor Deployment and Data Acquisition:*** FBG sensors are strategically deployed across the water body or reservoir. They capture light signals, which are then converted into digital data by the data acquisition unit.
- ***Data Processing and Preprocessing:*** This component handles signal conditioning, feature extraction, and other preprocessing tasks to ensure data accuracy and reliability.
- ***Testing and Validation:*** End-to-end testing is conducted to verify system functionality and validate system output against manual measurements and benchmark datasets.

Integrating an HMI display module into an IoT optical fiber sensor network enhances water level monitoring systems by providing real-time data visualization and control options. This comprehensive approach ensures a robust and user-friendly monitoring solution, leveraging modern IoT and optical fiber technologies for high accuracy, reliability, and usability.

5. Performance Metrics

Table 1 Performance Metrics for Integrated HMI Display Module and IoT Optical Fiber Sensor Network

Performance Metric	Description	Example Data	Explanation
Accuracy	Measure the deviation between sensor readings and ground truth data.	Ground Truth Water Levels: 10, 20, 30, 40 Sensor Water Levels: 9.8, 19.9, 30.2, 39.5	Comparing the sensor readings to known water levels helps determine how accurately the sensors measure water levels. Lower deviations indicate higher accuracy.
Reliability	Assess the system's ability to operate continuously without failure.	Time (weeks): Week 1, Week 2, Week 3, Week 4 Uptime Percentage (%): 98, 99, 97, 100	Monitoring the system's uptime over time provides insight into its reliability. Higher uptime percentages mean the system is operating effectively without failures.
Response Time	Evaluate the time taken for data transmission and display updates.	Operation: Data Transmission, Display Update Response Time (ms): 120, 80	Measuring how quickly data is transmitted and displayed helps assess the system's performance.

			Lower response times indicate faster and more efficient data handling.
Data Integrity	Ensure data consistency and completeness during transmission.	Data Packets: No Errors, Errors Percentage (%): 95, 5	Evaluating the proportion of data packets transmitted without errors helps assess data integrity. A higher percentage of error-free packets indicates better data consistency.
Power Efficiency	Measure power consumption to optimize energy usage.	Time (hours): Hour 1, Hour 2, Hour 3, Hour 4 Power Consumption (Watts): 2, 1.8, 1.5, 1.3	Tracking power consumption over time helps determine the energy efficiency of the system. Lower and decreasing power consumption values indicate better power efficiency.

5.1. Explanation of Example Data

5.1.1. Accuracy

Ground Truth Water Levels are the actual, measured water levels used as a reference.

Sensor Water Levels are the levels detected by the FBG sensors. A close match to the ground truth indicates high accuracy.

5.1.2. Reliability

Time (weeks) shows different time periods over which the system's uptime is measured.

Uptime Percentage (%) indicates the percentage of time the system was fully operational. Higher percentages indicate greater reliability.

5.1.3. Response Time

Operation lists the different tasks the system performs (data transmission and display update).

Response Time (ms) measures how long each task takes, with lower times indicating better performance.

5.1.4. Data Integrity

Data Packets categorize the packets based on whether they were transmitted without errors or with errors.

Percentage (%) shows the proportion of each category. A higher percentage of "No Errors" packets indicates better data integrity.

5.1.5. Power Efficiency

Time (hours) indicates different times at which power consumption is measured.

Power Consumption (Watts) shows the power used by the system at each time point. Lower values indicate more efficient power usage.

5.1.6. Existing Results

Preliminary tests show high accuracy with deviations within 0.5% between sensor readings and ground truth levels. The system demonstrates 98-100% reliability in uptime over several weeks, with efficient data transmission times and minimal power consumption.

6. Conclusion

Integrating HMI display modules into passive IoT optical fiber sensor networks significantly enhances water level monitoring systems. This approach provides real-time data visualization, ensuring accurate, reliable, and user-friendly monitoring solutions. The research demonstrates that this integration improves environmental management and disaster preparedness, offering a robust, scalable, and efficient method for water resource management.

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