Design and implementation of multi-sensor fusion real-time water pressure detection system

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Abstract: The traditional water pressure detection method relies on a single sensor, which has the problem of insufficient detection accuracy and stability. Therefore, this system integrates various types of sensors and adopts advanced data fusion algorithms, such as weighted average and D-S evidence theory, to comprehensively analyze the sensor data, so as to improve the detection accuracy and stability. The system adopts hierarchical design idea, including data acquisition layer, data fusion processing layer, data transmission layer and user interface layer. In the hardware part, STM32F407VGT6 microcontroller and ESP8266 Wi-Fi module are selected to ensure the efficient processing and stable transmission of the system. In software design, the lower computer is responsible for data acquisition and preprocessing, while the upper computer realizes data reception, storage, display, analysis and alarm. The experimental results show that the multi-sensor fusion measurement method shows higher detection accuracy and stability than a single sensor under different water pressure conditions, and the error range is significantly reduced. The system provides strong support for intelligent management in water supply system, building fire protection and industrial environment monitoring, and has broad application prospects.

1. Introduction

Traditional water pressure detection methods often rely on a single sensor to collect data. Although this method can meet the basic detection requirements to a certain extent, it is often difficult to ensure its detection accuracy, stability and reliability in the face of complex and changeable environmental conditions. Applying multi-sensor fusion technology to real-time water pressure detection system has become an effective way to improve detection performance [1]. Multi-sensor fusion technology can reflect the actual state of the measured object more comprehensively by synthesizing the data of multiple sensors, and effectively suppress the possible errors and interference of a single sensor, thus improving the overall detection accuracy and stability of the system [2].

A real-time water pressure detection system based on multi-sensor fusion is designed and implemented. The system integrates several different types of pressure sensors and uses advanced data fusion algorithm to process and analyze the sensor data, so as to realize real-time and accurate monitoring of water pressure. The implementation of this study not only helps to improve the performance of water pressure detection system, but also provides strong support for intelligent management in water supply system, building fire protection and industrial environment monitoring.

2. System overall design

2.1. System architecture

Figure 1 shows the system architecture of the design. This system is a real-time water pressure detection system based on multi-sensor fusion, and its overall architecture adopts hierarchical design idea, which is mainly divided into data acquisition layer, data fusion processing layer, data transmission layer and user interface layer. The data acquisition layer collects and preprocesses the water pressure data in real time through the pressure sensors distributed at each monitoring point, and then transmits it to the data fusion processing layer; As the core of the system, this layer comprehensively analyzes multi-source data by using algorithms such as weighted average or D-S evidence theory to improve the detection accuracy and stability [3-4]. The processed data can be sent to the user interface layer by wire or wireless through the data transmission layer to ensure smooth communication. This layer provides a concise and intuitive interface for users to view the data analysis results and alarm information, thus realizing a convenient operation experience.

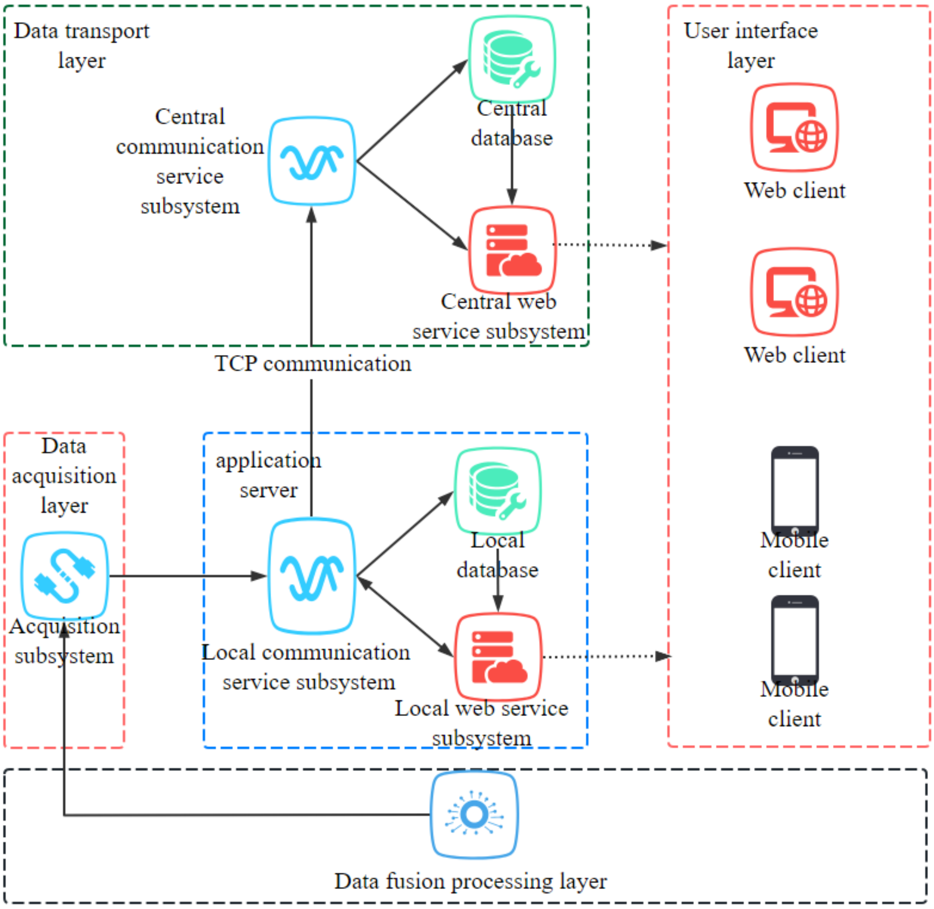

Figure 1 Architecture of real-time water pressure detection system based on multi-sensor fusion

2.2. Functional module division

The system consists of five main modules: the sensor module collects water pressure data in real time and converts it into electrical signals to be transmitted to the data acquisition and processing module; The latter preprocesses the received original data, such as filtering and amplifying, and sends the result to the data fusion module; The data fusion module comprehensively analyzes data from multiple sensors to improve accuracy and stability, and interacts with the communication module; The communication module ensures that the processed data is transmitted to the user interface layer in a wired or wireless way; Finally, the user interface module displays these data and provides data analysis and alarm functions, which is convenient for users to operate. Each module cooperates with each other to realize the collection, processing, analysis and display of water pressure data.

3. System hardware design

3.1. Sensor selection and layout

In this system, PT100 temperature sensor is selected to monitor the water temperature at the inlet of the water tank, PX30 pressure sensor is installed at the outlet of the water pump to monitor its working state and output pressure, and LWGY turbine flowmeter is installed on the main water pipe to monitor the water flow of the system. By arranging multiple sensors at key positions, such as pump outlet and water pipe bend, more accurate water pressure data can be collected, and effective monitoring of water temperature, water pressure and flow rate can be realized.

3.2. Hardware circuit design

Select the water pressure, temperature and flow sensor with high precision and quick response, and design the interface circuit according to its output type and communication protocol. The signal conditioning circuit is constructed to amplify, filter and linearize the sensor signal to ensure the purity and stability of the signal. Analog to digital signal is converted by A/D converter to prepare for subsequent data processing [5]. The core microcontroller is responsible for coordinating the work of sensors, executing data processing and fusion algorithms, and managing communication. The stable power supply circuit design ensures the reliable operation of the system, while the communication circuit selects wired or wireless mode to transmit data to the upper computer or cloud platform according to requirements. The display and alarm circuit is designed to provide real-time monitoring and alarm functions. In the stage of hardware layout and wiring, PCB design is carried out according to the principle of reducing interference and optimizing signal integrity.

3.3. Hardware selection and integration

The system selects STM32F407VGT6 microcontroller as the core processor (see Figure 2), which meets the requirements with its powerful processing power, rich peripheral interfaces and low power consumption. STM32F407VGT6 microcontroller, 32-bit, Ethernet MAC, camera interface, ARM cortex -M4, 168 MHz, 1 MB, 196 KB, 100 pins, LQFP. Table 1 shows its detailed specifications.

Table 1 Product specification parameter list

Specification item	Parameter
RoHS standard	RoHS Compliant
Lead standard	Lead Free
product life cycle	Active
manner of packing	Tray
REACH SVHC standard	No SVHC
Installation mode	Surface Mount
length	14.2 mm
frequency	168 MHz
Pin number	100 Pin
width	14.2 mm
Power supply voltage	1.80V (min)
height	1.45 mm
operating voltage	1.8V ~ 3.6V
encapsulation	LQFP-100
Working temperature	-40℃ ~ 85℃ (TA)
Number of pins	100 Position
clock frequency	168 MHz
RAM size	196 KB
digit capacity	32 Bit
FLASH memory capacity	1 MB
ADC number	3 ADC
ECCN code	3A991A2
Input/output number	82 Input
Operating temperature (Max)	85 ℃
Working temperature (Min)	-40 ℃
Digital-analog conversion number	1 DAC
Power supply voltage	1.8V ~ 3.6V
Power supply voltage (Max)	3.6 V
Power supply voltage (Min)	1.8 V
Industrial grade	Yes
Medical grade	Yes

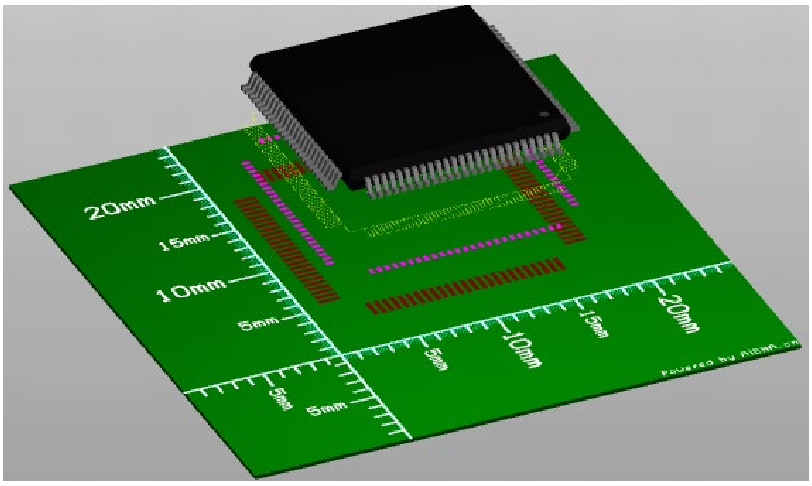

Figure 2 Perspective view of STM32F407VGT6 microcontroller

ESP8266 Wi-Fi module is selected to realize stable and real-time wireless data transmission. According to the circuit design requirements, passive components such as resistors, capacitors and inductors with appropriate specifications are selected to ensure the circuit performance and stability. In the hardware integration stage, all the selected components are rationally laid out and wired according to the design, and anti-interference design is emphasized, and the integrated system is fully debugged and tested to ensure its normal work and performance standards.

4. System software design

4.1. Software design of lower computer

The lower computer software focuses on the collection and preprocessing of sensor data to ensure the accuracy and reliability of the data. Its core function is to set an appropriate sampling rate and resolution by configuring the ADC module of the microcontroller, so as to read and convert the analog water pressure signals of each sensor into digital signals in real time.

Pseudo code:

```
void initADC() {
        // Initialize ADC module
        //Set parameters such as sampling rate and resolution
}

int readSensorData(int sensorID) {
        // Select the corresponding ADC channel according to the sensor ID
        // Start ADC conversion and wait for the conversion to complete
        // Read the conversion result and return the digital signal
}

void collectData() {
        int sensor1Data = readSensorData(1);
        int sensor2Data = readSensorData(2);
        // ... Collect data from other sensors
}
```

4.2. Data preprocessing program

Pre-processing operations such as filtering and calibration are carried out on the collected original data. Digital filtering algorithm is used to remove noise, and the data is calibrated according to the calibration parameters of the sensor. Pseudo code:

```
int filterData(int rawData) {
```

```
        // Implement digital filtering algorithm
        // Returns the filtered data
}

int calibrateData(int filteredData, int sensorID) {
        // Obtaining calibration parameters according to the sensor ID
        // Calibrate the filtered data
        // Return the calibrated data
}

void preprocessData() {
        int rawSensor1Data = readSensorData(1);
        int filteredSensor1Data = filterData(rawSensor1Data);
        int calibratedSensor1Data = calibrateData(filteredSensor1Data, 1);
        // ... Preprocessing the data of other sensors
}
```

4.3. Software design of upper computer

The software design of the upper computer covers the functions of data receiving, storage, display, analysis and alarm, and uses Python programming language and corresponding development framework to build the user interface. By configuring the communication interface and parameters, the software can receive the data transmitted by the lower computer through serial port or network, and read and analyze these data regularly to ensure its timeliness and availability. The code implementation is adjusted according to the selected language and communication mode, and the corresponding data receiving program is written in Python.

```
import serial

def receiveData():
        ser = serial.Serial('COM1', 9600)    # Configure serial port parameters
        while True:
                if ser.in_waiting > 0:
                        data = ser.readline().decode('utf-8')    # Read data
                        processData(data)    # Parse and process data

def processData(data):
        # Analyze the data and extract the values of each sensor
        # ...
```

The data storage program is responsible for saving the received data to the selected database (such as SQLite and MySQL) or file (such as CSV and TXT) on a regular basis, and designing the appropriate data structure. The data display program uses chart controls (Matplotlib, QtCharts) to draw the graph or dashboard of sensor water pressure data in real time. The data analysis and alarm program detects the abnormal situation or the phenomenon exceeding the set threshold by analyzing the stored data, and triggers the alarm by means of sound, light or pop-up window to remind users to pay attention.

4.4. Implementation of data fusion algorithm

Data fusion algorithms such as membership center method, weighted average method and D-S evidence theory are realized in the upper computer software to improve the detection accuracy and stability [6-7]. The following is a brief implementation example of the membership center method:

In the realization of membership center method, the fused water pressure value is calculated according to the membership function of each sensor. Define the membership function of each sensor, calculate the membership value of each sensor, and calculate the fused water pressure value according to the membership value.

Code example (Python):

```
def membershipFunction(sensorValue, params):
    # Calculate membership degree according to sensor values and parameters
    # Returns the membership value (between 0 and 1)

def fuseData(sensorDataList, membershipParamsList):
    fusedValue = 0.0
    totalWeight = 0.0
    for i, sensorData in enumerate(sensorDataList):
        membershipValue = membershipFunction(sensorData, membershipParamsList[i])
        fusedValue += membershipValue * sensorData    # Weighted summation
        totalWeight += membershipValue    # Total weight
    return fusedValue / totalWeight    # Calculate the water pressure value after fusion

# Example usage
sensorDataList = [10, 12, 9]    # Water pressure data of each sensor
membershipParamsList = [[...], [...], [...]]    # Membership function parameters of each sensor
fusedValue = fuseData(sensorDataList, membershipParamsList)
print("Water pressure value after fusion:", fusedValue)
```

Similarly, other data fusion algorithms such as weighted average method and D-S evidence theory can be realized. In practical application, it is necessary to select the appropriate algorithm according to the specific detection requirements and sensor characteristics, and optimize the parameters and test the performance of the algorithm to ensure the accuracy and stability of the fusion results.

5. Experimental test

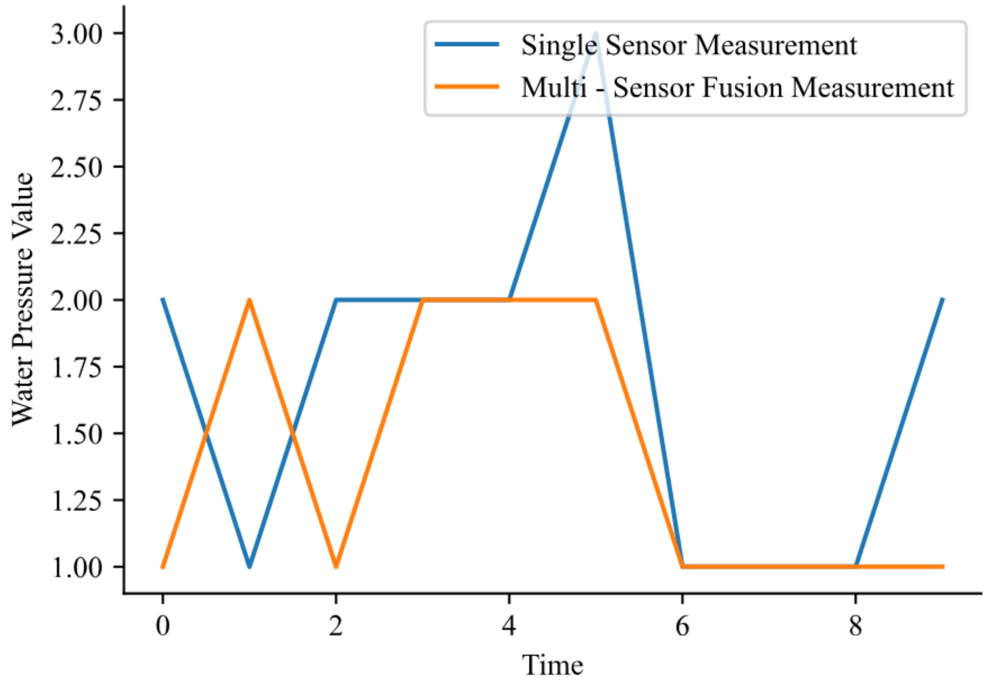

Figure 3 Trend of water pressure changing with time

Several groups of experiments were designed to test the detection effect of the system under different water pressure conditions. Each group of experiments adopts single sensor measurement and multi-sensor fusion measurement for comparison. The experimental results show that the multi-sensor fusion measurement method has higher detection accuracy and stability than the single sensor measurement method (see Figure 3). In many experiments, the multi-sensor fusion measurement method can accurately capture the change of water pressure and output stable and reliable water pressure values. Compared with the traditional water pressure detection system, and verified by the results of several groups of experiments, the superiority of multi-sensor fusion technology in real-time water pressure detection system is fully proved. Multi-sensor fusion technology can effectively improve the detection accuracy and stability of the system and provide more accurate and reliable data support for real-time monitoring of water pressure.

Table 2 Comparison of hydraulic pressure measurement accuracy

Water pressure condition (MPa)	Measured value of single sensor (MPa)	Multi-sensor fusion measurement (MPa)	Single sensor error (%)	Multi-sensor fusion error (%)
0.1	0.102	0.101	2.0	1.0
0.5	0.515	0.503	3.0	0.6
1.0	1.020	1.005	2.0	0.5
1.5	1.530	1.507	2.0	0.46
2.0	2.045	2.010	2.25	0.5
2.5	2.560	2.515	2.4	0.6
3.0	3.075	3.020	2.5	0.67

Table 2 shows that multi-sensor fusion measurement shows higher accuracy and stability than single sensor measurement under different water pressure conditions. Specifically, the error percentage of multi-sensor fusion is always lower than that of a single sensor, and its error range is only 0.46% to 0.67%, which is significantly lower than that of a single sensor of 2.0% to 2.5%. This shows that by fusing the data of multiple sensors, the measurement error is effectively reduced, and the reliability and accuracy of water pressure detection are greatly improved.

Through multi-sensor fusion technology and optimized hardware design, the system realizes real-time and accurate detection of water pressure. The system performs well in practical application, with high detection accuracy and stability. At the same time, the application effect of multi-sensor fusion technology has been fully verified, which provides strong support for the further promotion and application of the system.

6. Conclusion

In this study, a real-time water pressure detection system based on multi-sensor fusion is designed and implemented. By integrating multiple sensors and adopting advanced data fusion algorithm, the accuracy and stability of water pressure detection are effectively improved. The experimental results show that the error range of multi-sensor fusion is reduced from 2.0%-2.5% to 0.46%-0.67%, which greatly reduces the measurement error and enhances the reliability and stability of the system. In this system, STM32F407VGT6 microcontroller and ESP8266 Wi-Fi module are used for data processing and wireless transmission respectively, and signal integrity and anti-interference ability are ensured by optimizing hardware circuit design. The software part realizes the functions of data receiving, storage, display, analysis and alarm from sensor data collection to upper computer, and constructs a user-friendly interface with Python language. This study provides strong technical support for intelligent management in water supply system, building fire protection and industrial environment monitoring.

Acknowledgments

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