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Design and Implementation of Real time Detection System for Indoor Air Quality under Multiple Environmental Temperature Conditions

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Abstract

This study aims to design and implement a real-time monitoring system for in car air quality suitable for multiple environmental temperature conditions, in order to improve the level of air quality monitoring in driving environments. the basic principles of air quality detection and the impact of different environmental temperatures on the characteristics of air pollutants in vehicles were analyzed, and the hardware selection and design considerations of the system were determined. On this basis, an analysis method for the impact of temperature on the accuracy of air quality sensors was proposed, and algorithms for data acquisition, real-time processing, temperature compensation, and multi-sensor data fusion were designed. The hardware implementation of the system includes sensor modules, data processing modules, and communication modules, while the software architecture covers real-time data processing and communication protocol design. The accuracy and stability of the system were verified through experiments under multiple environmental temperature conditions. The experimental results show that the system can effectively monitor the air quality inside the vehicle and accurately compensate for the concentration of pollutants under different temperature conditions, with good application prospects. This study provides a technical foundation and reference for further optimization and promotion of the in car air quality monitoring system.

Keywords

Air quality inside the car; Real time detection; Multiple environmental temperatures; Temperature compensation; Multi sensor data fusion.

1. INTRODUCTION

With the improvement of living standards and the growing awareness of environmental protection, air quality issues have received increasing attention. In particular, the air quality inside vehicles—an enclosed environment—directly affects the health and safety of drivers and passengers. However, in-vehicle air quality is easily influenced by various factors such as external environmental conditions, the release of harmful gases from interior materials, and passenger activities. These effects can become even more pronounced under different temperature conditions.

Traditional in-vehicle air quality detection systems typically operate under fixed environmental settings, making it difficult to fully reflect the variation in pollutant concentrations under changing temperature conditions. Moreover, many existing systems merely detect pollutant levels without conducting in-depth sensor data analysis or applying temperature compensation, resulting in reduced accuracy under extreme temperatures[1].

This study aims to design and implement a real-time in-vehicle air quality detection system capable of accurately monitoring the concentrations of major air pollutants under various temperature conditions. To achieve this, it is first necessary to analyze the behavior of common in-vehicle air pollutants across different temperatures and to select appropriate hardware components for the system, including air quality sensors, data processing modules, and communication modules.

2. DESIGN BASIS OF THE IN-VEHICLE AIR QUALITY REAL-TIME DETECTION SYSTEM

2.1. Basic Principles of Air Quality Detection

The basic principle of air quality detection involves the real-time monitoring of pollutant concentrations in the air using sensors, converting the acquired signals into electrical signals, and then processing them with corresponding algorithms to obtain specific concentration values. Common indoor air pollutants include volatile organic compounds (VOCs), carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO), and particulate matter (PM2.5, PM10).

The core of air quality detection lies in utilizing the response characteristics of sensors to measure pollutant levels. Common detection techniques include electrochemical methods, optical methods, metal oxide semiconductor (MOS) methods, and infrared absorption methods. For example, electrochemical sensors operate based on redox reactions at the sensing electrode, generating an electrical current that is proportional to the concentration of the target pollutant. The principle can be expressed as:

$$\mathrm{I} = \mathrm{nFv} \tag{1}$$

In the above equation, I represents the generated current, n is the number of electrons transferred, F is the Faraday constant, V denotes the reaction volume. Optical sensors are commonly used for particulate matter detection. Based on the principle of light scattering, when a light beam passes through air containing particulate matter, scattering occurs. The intensity of the scattered light is proportional to the concentration of the particles. By measuring the intensity of the scattered light, the particle concentration can be calculated. The relationship can be expressed as follows:

$$\mathrm{I}_{\mathrm{scatter}} = \mathrm{I}_0 \times \mathrm{e}^{-\alpha \cdot \mathrm{C} \cdot \mathrm{d}} \tag{2}$$

In the above equation, $\mathrm{I}_{\mathrm{scatter}}$ represents the intensity of the scattered light, I_0 is the intensity of the incident light, α denotes the absorption coefficient, C is the concentration of the particulate matter, and d is the optical path length.

2.2. Characteristic Analysis of In-Vehicle Air Pollutants Under Different Environmental Temperature Conditions

Under different environmental temperature conditions, the concentration and behavior of in-vehicle air pollutants exhibit significant variations. Temperature has a direct impact on the emission of volatile organic compounds (VOCs); generally, elevated temperatures accelerate the release of VOCs from interior materials, leading to the deterioration of in-vehicle air quality. The specific data are shown in Table 1 below.

Table 1. Concentration of In-Vehicle Air Pollutants Under Different Temperature Conditions

Temperature (°C)	CO_2 (ppm)	VOCs (ppb)	PM2.5 (μg/m^3)	Formaldehyde (ppb)
10	400	120	10	15
15	420	150	12	18
20	450	200	14	25
25	470	260	16	35
30	500	320	18	45
35	530	400	20	60
40	570	500	22	80

As shown in Table 1, the concentrations of CO_2, VOCs, PM2.5, and formaldehyde inside the vehicle all increase with rising temperature. Specifically, the concentration of CO_2 gradually increases from 400 ppm at 10 °C to 570 ppm at 40 °C. This rise may be attributed to an increased respiratory rate of occupants at higher temperatures and decreased air circulation within the vehicle[2].

In addition, the VOCs concentration is approximately 120 ppb at low temperatures, but it rises sharply to 500 ppb at 40 °C. This phenomenon can be explained by the intensified release of volatile organic compounds from interior materials under high-temperature conditions.

For PM2.5, the concentration increases from 10 μg/m^3 at 10 °C to 22 μg/m^3 at 40 °C, which may be due to the enhanced suspension and accumulation of particles in warmer environments. The variation in formaldehyde concentration is also notable, rising from 15 ppb at low temperatures to 80 ppb at high temperatures, indicating that formaldehyde emission is strongly temperature-dependent.

2.3. System Components and Design Analysis of the In-Vehicle Air Quality Detection System

The overall structure of the in-vehicle air quality detection system can be analyzed from several key components. The sensor module serves as the core of the system, primarily responsible for monitoring the concentration of pollutants inside the vehicle. Common air pollutants include carbon dioxide (CO_2), volatile organic compounds (VOCs), PM2.5, and formaldehyde. To ensure monitoring accuracy, dedicated sensors are selected for each type of pollutant—for example, CO_2 sensors adopt non-dispersive infrared (NDIR) technology, VOCs and formaldehyde are measured using electrochemical sensors, and PM2.5 detection relies on laser scattering-based sensors.

The data processing module is responsible for receiving and processing signals from multiple sensors in real time. This module is typically built on a low-power embedded processor, such as the ARM Cortex series. These processors provide sufficient computational power to execute data fusion and temperature compensation algorithms. Data fusion techniques combine readings from multiple sensors to generate a comprehensive assessment of in-vehicle air quality, while temperature compensation algorithms correct for sensor errors caused by ambient temperature variations, ensuring high measurement accuracy under different environmental conditions[3].

The communication module transmits the processed air quality data to external devices or cloud platforms for further analysis and storage. Wireless communication technologies such as Wi-Fi or Bluetooth are commonly used to achieve this functionality, ensuring the system can seamlessly exchange data with external networks at any time.

The power module supplies stable electrical power to the system. It typically integrates with the vehicle's onboard power system and uses voltage step-down and regulation circuits to convert the 12V vehicle power supply into voltages suitable for the operation of sensors and processors. The system design also incorporates low-power management functions, enabling the system to enter a low-power mode when the vehicle is stationary, thereby extending operational lifespan[4].

3. ALGORITHM DESIGN FOR IN-VEHICLE AIR QUALITY MONITORING UNDER MULTIPLE ENVIRONMENTAL TEMPERATURE CONDITIONS

3.1. Analysis of Temperature Effects on Air Quality Sensor Accuracy

Temperature is one of the key factors affecting the accuracy of air quality sensors. The response characteristics of sensors may vary significantly under different temperature conditions, which can impact the reliability of the detection results.

For electrochemical sensors, temperature changes directly influence the electrochemical reaction rates at the electrodes, thereby altering the output signal of the sensor. The accuracy of optical sensors is also sensitive to temperature, especially in particulate matter detection. Temperature variations can change the refractive index of optical components, which in turn affects light scattering behavior and measurement outcomes.

Moreover, temperature fluctuations may cause performance instability in the electronic components within the sensor, such as resistors and capacitors, whose electrical parameters may drift with temperature changes. These variations can collectively degrade the overall accuracy of the sensor.

The measurement deviation of a certain model of CO_2 sensor under different temperature conditions is shown in Table 2.

Table 2. Detection Deviation of CO_2 Sensor Under Different Temperature Conditions

Temperature (°C)	Actual Concentration (ppm)	Measured Concentration (ppm)	Deviation (%)
20	450	450	0
25	450	460	2.22
30	450	475	5.56
35	450	490	8.89
40	450	500	11.11

3.2. Design of Data Acquisition and Real-Time Processing Algorithms

In an in-vehicle air quality monitoring system, the design of data acquisition and real-time processing algorithms is critical to ensuring both responsiveness and accuracy. The data acquisition process involves collecting real-time data from multiple sensors and analyzing it through algorithms to deliver accurate assessments of air quality. The algorithm design for data acquisition and processing typically follows these steps:

Sensor Data Acquisition: The system collects real-time data from multiple sensors, including CO_2, VOCs, PM2.5, and formaldehyde sensors.

Data Preprocessing: The raw data acquired often contains noise and outliers, which must be filtered or corrected through preprocessing techniques to ensure data reliability.

Multi-Sensor Data Fusion: After preprocessing, data from different sensors are fused to generate a more comprehensive and integrated evaluation of in-vehicle air quality.

Real-Time Data Analysis: The fused data are then used for real-time analysis to assess the current air quality conditions inside the vehicle.

3.3. Temperature Compensation and Multi-Sensor Data Fusion Algorithms

In air quality monitoring systems, the basic principle of temperature compensation is to correct sensor errors caused by temperature variations using compensation functions or models. Common temperature compensation methods include linear compensation, nonlinear compensation, and model-based compensation.

Linear compensation is the simplest approach and is applicable when there is a linear relationship between temperature and sensor error. Nonlinear compensation is suitable for more complex, non-linear behaviors. Model-based compensation involves building a mathematical model that describes the relationship between temperature and sensor output, and then correcting the output signal using that model. The general form of the model-based compensation formula is as follows:

$$C_{\text{corrected}} = C_{\text{measured}} - k \cdot (T - T_0) \tag{3}$$

In the above equation, $\mathrm{C}_{\text{corrected}}$ represents the temperature-compensated concentration value, $\mathrm{C}_{\text{measured}}$ is the measured (uncompensated) value, k denotes the temperature compensation coefficient,T is the current temperature, and T_0 is the reference temperature.

The purpose of the multi-sensor data fusion algorithm is to integrate data from different sensors to enhance monitoring accuracy and reliability. Kalman filtering is a commonly used data fusion algorithm that estimates the system state by combining current measurements with historical data to minimize estimation errors. The state update equation of the Kalman filter is given as:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k\left(y_k - H\hat{x}_{k|k-1}\right) \tag{4}$$

In the above equation,$\hat{\mathrm{x}}_{\mathrm{k|k}}$ denotes the updated state estimate, $\hat{\mathrm{x}}_{\mathrm{k|k-1}}$ is the prior estimate, K_k represents the Kalman gain, y_k is the measurement value, and H is the observation matrix. The calculation of the Kalman gain depends on the error covariance matrix, which allows the gain to be dynamically adjusted. This enables optimal fusion of multi-sensor data, thereby improving the accuracy and stability of air quality monitoring.

4. IMPLEMENTATION AND TESTING OF THE REAL-TIME DETECTION SYSTEM

4.1. Hardware Implementation of the Detection System

The hardware implementation forms the foundation of the air quality monitoring system. The hardware design integrates the sensor module, data processing module, communication module, and power management module. The sensor module consists of a variety of sensors, including a non-dispersive infrared (NDIR) $\mathrm{CO_2}$ sensor, an electrochemical VOCs sensor, a laser-scattering PM2.5 sensor, and an electrochemical formaldehyde sensor. Each sensor is connected to the main control board via dedicated interfaces to ensure stable signal transmission and accurate data acquisition.

The data processing module employs an ARM Cortex-M series microcontroller, which offers high performance and low power consumption, enabling real-time processing of signals from all sensors and executing complex algorithms such as temperature compensation and data fusion.

The power management module is designed in consideration of the vehicle's power environment. A step-down voltage regulator converts the vehicle’s 12V power supply into appropriate voltages required by the microcontroller and sensors. The system also integrates a power management unit to enable low-power mode switching, thereby extending operational life.

4.2. System Software Architecture and Communication Protocol Design

The software architecture and communication protocol design are crucial to the efficient operation of the detection system. A layered software architecture is adopted, including the data acquisition layer, data processing layer, communication layer, and user interface layer. The design is structured as follows:

In the data acquisition layer, the system uses interrupt-driven mechanisms to acquire real-time data from each sensor module. The sampling frequency is optimized according to the sensor response rates and system requirements.

The data processing layer performs multi-sensor data fusion and temperature compensation on the acquired data.

The user interface layer includes a mobile-based application that allows users to view real-time in-vehicle air quality data and receive alerts and recommendations from the system.

4.3. Experiments and Data Analysis Under Multiple Environmental Temperature Conditions

Rigorous experiments were conducted under multiple environmental temperature conditions to verify the system’s performance and stability. The experiments were performed at various temperature intervals: 10 °C, 20 °C, 30 °C, 40 °C, and 50 °C, simulating different in-vehicle air pollution scenarios at each temperature point.

During the tests, real-time data on CO_2, VOCs, PM2.5, and formaldehyde concentrations were recorded and compared with measurements obtained from standard reference instruments. The detection error between the developed system and the standard device under different temperature conditions is summarized in Table 3.

Table 3. Error Analysis Between the System and Standard Device Under Different Temperature Conditions

Temperature (°C)	CO_2 Detection Error (ppm)	VOCs Detection Error (ppb)	PM2.5 Detection Error (μg/m^3)	Formaldehyde Detection Error (ppb)
10	5	10	1	2
20	7	12	2	3
30	10	15	3	4
40	12	20	4	6
50	15	25	5	8

The experimental results indicate that as temperature increases, the system's detection error tends to rise, with more significant deviations observed under high-temperature conditions. This phenomenon is closely related to the effect of temperature on sensor accuracy. However, after applying the temperature compensation algorithm, the detection accuracy of the system was significantly improved.

For example, under high-temperature conditions at 50 °C, the CO_2 detection error was reduced from 25 ppm (before compensation) to 15 ppm (after compensation), and the VOCs detection error decreased from 35 ppb to 25 ppb. Similarly, the PM2.5 and formaldehyde detection errors were reduced from 8 μg/m^3 and 10 ppb to 5 μg/m^3 and 8 ppb, respectively.

These experimental results validate the effectiveness of the temperature compensation and multi-sensor data fusion algorithms, demonstrating that the system can maintain high detection accuracy under varying temperature conditions.

5. SYSTEM PERFORMANCE OPTIMIZATION AND APPLICATION PROSPECTS

5.1. System Performance Optimization Based on Experimental Data

Based on the experimental data under multiple environmental temperature conditions, system optimization efforts are mainly focused on sensor calibration, temperature compensation algorithm refinement, and data processing enhancement. The experimental results show that although the system mitigated part of the detection errors at higher temperatures through the temperature compensation algorithm, there was still a degree of cumulative error—particularly in the detection accuracy of VOCs and formaldehyde, which showed considerable deviations under high-temperature conditions.

To address this, more precise calibration of individual sensors is required, especially to account for zero drift and sensitivity variation across temperature ranges. Additionally, the temperature compensation algorithm can be further improved by incorporating nonlinear regression models to more accurately fit the relationship between temperature and sensor output, thereby enhancing compensation accuracy under high-temperature scenarios.

5.2. Application Performance Analysis in Real-World Driving Environments

Field tests in real-world driving environments indicate that the system can effectively monitor in-vehicle air quality and respond in a timely manner to fluctuations in pollutant concentrations. The testing scenarios included urban roads, highways, and tunnels, among others. Across various driving conditions, the system demonstrated high stability and reliability.

The comparison between system-detected air quality data and actual environmental monitoring results in different driving scenarios is shown in Table 4.

Table 4. Comparative Analysis of In-Vehicle Air Quality Data in Different Driving Scenarios

Driving Scenario	CO_2 Concentration (ppm)	VOCs Concentration (ppb)	PM2.5 Concentration ($\mu g/m^3$)	Formaldehyde Concentration (ppb)	AQI
Urban Road	500	250	30	40	75
Highway	450	200	25	35	68
Tunnel Driving	700	400	50	60	120
Idling with Air Conditioning On	650	300	45	50	98
Idling without Air Conditioning	800	350	55	70	135

As shown in Table 4, pollutant concentrations such as CO_2, VOCs, PM2.5, and formaldehyde are significantly higher during tunnel driving and idling conditions, compared to urban or highway driving. This is likely due to poor ventilation in tunnels and reduced air circulation while the vehicle is stationary, leading to the accumulation of indoor pollutants.

5.3. System Scalability and Future Application Directions

The scalability of the detection system is primarily reflected in three aspects: expansion of sensor modules, enhancement of data processing capabilities, and integration with other in-vehicle systems. With the continuous advancement of sensor technology, the system can be expanded in the future to include additional types of air quality sensors—such as those for ozone (O_3) and nitrogen oxides (NOx)—to enable more comprehensive in-car air quality monitoring.

Improvements in data processing capabilities can be achieved by adopting higher-performance processors and incorporating cloud computing platforms, allowing the system to handle more complex data and support advanced algorithms. For example, artificial intelligence (AI) and machine learning (ML) techniques can be used for pattern recognition and predictive analysis.

Furthermore, the system can be integrated with other vehicle intelligent systems, such as the in-vehicle navigation system, automatic air conditioning system, and vehicle-to-everything (V2X) platforms, to achieve a more intelligent and automated air quality management system.

6. CONCLUSION

This study designed and implemented a real-time in-car air quality monitoring system adaptable to multiple environmental temperature conditions. Through careful hardware selection, software architecture design, and optimization of temperature compensation and multi-sensor data fusion algorithms, the system's detection accuracy and stability under varying temperature conditions have been significantly improved.

Experimental data show that the system effectively corrects sensor temperature drift under high-temperature conditions, ensuring accurate detection of key pollutants such as CO_2, VOCs, PM2.5, and formaldehyde. Field testing in real-world driving environments further confirmed the system's reliability and practicality, demonstrating its ability to provide real-time monitoring and intelligent management of in-car air quality across complex driving scenarios.

The proposed system not only improves the precision and responsiveness of in-vehicle air quality monitoring but also exhibits strong scalability and promising future applications. It offers valuable technical support and reference for the development of intelligent vehicular systems and the broader advancement of smart city infrastructure.

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