ISSN: 2688-8645

Construction and Empirical Study of an Evaluation System for Automotive Touch Interaction Performance in Extreme Temperature Environments

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Abstract

To address the issues of easy performance degradation of automotive touch interaction systems in extreme temperature environments and the lack of targeted evaluation in existing systems, this study develops an evaluation system for automotive touch interaction performance in extreme temperature environments. First, through literature analysis, the composition and working principles of automotive touch interaction systems are sorted out, and combined with case studies, the influence mechanisms of extreme temperatures on the hardware materials, electronic components, and software stability of touch systems are analyzed. Second, aiming at the defects of incomplete index coverage and imperfect methods in existing evaluation systems for extreme temperature scenarios, experience from temperature evaluation in the electronic equipment and aerospace fields is drawn upon. Twelve core evaluation indicators are selected and optimized from three dimensions: hardware performance, software stability, and human-computer interaction experience. Test methods and standardized procedures for high temperature (50-85℃), low temperature (-40 to -10℃), and temperature shock (-40℃→85℃ cycle) are designed, and a five-level performance evaluation standard is formulated. Finally, empirical tests are conducted on three different vehicle models. Variance analysis and correlation analysis are used to verify the validity of the indicators. The results show that this system can accurately quantify the variation rules of key performance parameters such as touch response delay and recognition accuracy under extreme temperatures, with the recognition error rate reduced by 18.3% compared with traditional evaluation methods. The constructed evaluation system fills the technical gap in the evaluation of automotive touch interaction performance under extreme temperature scenarios and provides standardized technical support for the temperature-resistant design optimization and performance verification of automotive touch systems.

Keywords

Automotive Touch; Extreme Temperature Environment; Human-Computer Interaction; Evaluation.

1. Introduction

In the wave of automotive intelligence, the intelligent cockpit has become a key field for the innovative development of the automotive industry. As a core component of human-computer interaction in the intelligent cockpit, the touch interaction system is playing an increasingly important role. With the rapid development of science and technology, consumers have put forward higher requirements for the functions and experience of automotive intelligent cockpits. The touch interaction system, with its convenient and intuitive operation characteristics, has become a key link to improve the user experience. From simple multimedia

ISSN: 2688-8645

control to complex vehicle settings, and from navigation operations to the use of infotainment systems, the touch interaction system runs through various driving scenarios, and its performance directly affects the user's satisfaction with the entire intelligent cockpit and even the whole vehicle.

However, as a means of transportation used in various complex environments, automobiles face many environmental challenges, among which the impact of extreme temperatures on the performance of automotive touch interaction systems is particularly significant. In hot summers, when vehicles are exposed to the sun for a long time, the internal temperature of the vehicle may reach 60℃ or even higher. In cold winters, especially in high-latitude areas or extremely cold environments, vehicles may face low temperatures below -30℃. Under these extreme temperature conditions, both the hardware and software performance of the touch interaction system may be seriously affected, leading to problems such as slow response of the touch screen, insensitivity to touch, and system crashes. These problems not only reduce the user experience but also may affect driving safety at critical moments. For example, in a low-temperature environment, if the touch screen fails to respond promptly to the driver's operation of the defrosting function, it may block the line of sight and increase the risk of accidents. Therefore, it is of great significance to construct a scientific and comprehensive evaluation system for automotive touch interaction performance in extreme temperature environments [1].

From the perspective of automobile manufacturers, accurately evaluating the performance of touch interaction systems under extreme temperatures helps to identify problems in a timely manner during the product development stage, optimize the design, improve product quality and reliability, and enhance market competitiveness. For consumers, the establishment of an evaluation system can provide a reference for their car purchase decisions, enabling them to choose vehicle models with more stable performance in extreme temperature environments. From the perspective of industry development, a sound evaluation system is conducive to promoting the progress of the entire automotive touch interaction technology, promoting the formulation and improvement of relevant standards, regulating market order, and driving the healthy development of the automotive intelligent cockpit industry.

2. Automotive Touch Interaction System and the Principle of Extreme Temperature Influence

2.1. Automotive Touch Interaction System

As a core interaction component of the intelligent cockpit, the automotive touch interaction system is mainly composed of a touch display screen, a touch screen controller, and related software systems. The touch display screen is the interface directly operated by the user, responsible for displaying various types of information, such as vehicle status, navigation maps, and multimedia content, while sensing the user's touch operations. The common types of touch display screens on the market currently include capacitive touch screens and resistive touch screens.

2.2. Influence Mechanism of Extreme Temperatures on Touch Interaction Performance

Extreme temperature environments have a multi-faceted impact on the performance of automotive touch interaction systems, involving multiple levels of hardware and software. In terms of hardware, both high and low temperatures have a significant impact on the material properties of touch screens and the performance of electronic components.

In a high-temperature environment, the material properties of the touch screen change. For capacitive touch screens, high temperatures may cause the resistance value of the internal ITO

ISSN: 2688-8645

coating to change, thereby affecting the stability of the capacitor and causing capacitor drift. Capacitor drift can lead to deviations in the positioning of touch points by the touch screen, resulting in inaccurate touch operations. For example, when the user clicks on an icon, the system may mistakenly judge it as clicking on another position. High temperatures also reduce the response speed of the touch screen. This is because high temperatures increase the resistance of semiconductor components (such as processors and touch control chips), reduce electron mobility, and cause the processing speed to slow down. The system may activate an overheating protection mechanism (thermal throttling) and actively reduce the operating frequency to reduce heat generation, which directly manifests as operation lag and response delay. This is unacceptable for automotive interaction operations that require real-time control and precise input, and may lead to operational errors or safety hazards during driving. For liquid crystal panels, high temperatures accelerate the aging of liquid crystal materials, leading to screen yellowing, brightness attenuation, and even "screen burn-in" phenomenon, which affects the display effect and service life. This not only reduces the user experience but also may affect the driver's reading of important information and increase driving risks [2].

In a low-temperature environment, touch screens also face many problems. The touch layer of capacitive touch screens may be affected. Due to the decrease in temperature, the conductivity of the material decreases, resulting in reduced touch sensitivity, and problems such as slow and insensitive touch occur. The driver may need to touch multiple times or press hard to achieve the operation, which distracts attention during driving and increases the difficulty and risk of operation. Low temperatures also affect the response speed of the liquid crystal screen, leading to screen trailing or slow refreshing, which affects the display effect. Especially when the vehicle is moving, rapidly changing information may not be displayed clearly in a timely manner, affecting the driver's judgment. In addition, if the automotive touch interaction system works in an extremely cold environment and is then suddenly exposed to a high-temperature environment, the thermal expansion and contraction of materials may cause cracks on the screen surface, damage the screen, and make the touch interaction system unable to work normally.

Electronic components are also affected under extreme temperatures. High temperatures may cause the performance parameters of electronic components to drift, such as changes in the values of capacitors and resistors, which affect the normal operation of the circuit and lead to system failures. Low temperatures may deteriorate the starting characteristics of electronic components, or even prevent them from starting normally. For example, some chips may take a longer time to reach a normal working state at low temperatures or cannot start directly, resulting in the inability to use the touch interaction system [3].

In terms of software, extreme temperatures also have an impact. In a high-temperature environment, the software system may experience problems such as memory leaks and crashes. Due to the increase in temperature, hardware performance decreases, and the software may fail to release memory in a timely manner during operation, leading to a continuous increase in memory usage and eventually memory leaks, which makes the system run slowly or even crash. In a low-temperature environment, the startup speed of the software slows down. Because the initialization process of the hardware is affected at low temperatures, the software loading time is prolonged, and the user needs to wait longer to use the functions of the touch interaction system.

3. Analysis of the Automotive Touch Interaction Performance Evaluation System

In a normal environment, the evaluation indicators of automotive touch interaction performance mainly focus on hardware performance and interaction experience. In terms of

ISSN: 2688-8645

hardware performance, response time is a key indicator, which refers to the time interval from when the user touches the screen to when the system responds and feeds back the result, usually measured in milliseconds (ms). The shorter the response time, the higher the fluency and immediacy of user operations, which can improve the user experience. Touch accuracy is also an important indicator, which measures the ability of the touch screen to accurately identify the position of the touch point, usually expressed by the error range, such as ±1mm. Low touch accuracy may lead to user operation errors and affect the user experience.

In terms of interaction experience, the main considerations are operational convenience and interface friendliness. Operational convenience is reflected in the steps and time required for users to complete common operations (such as navigation settings and music playback control). The fewer steps and the shorter the time, the higher the convenience. For example, through a concise and intuitive interface design, users can quickly find and click the required function buttons, and call the functions without complex menu searching and operations. Interface friendliness involves interface layout, color matching, icon design, etc. A friendly interface can make users feel comfortable and natural during operation, reducing operational errors and fatigue. For example, an ergonomic interface layout is adopted, with commonly used function buttons placed in easily touchable positions, and clear and eye-catching icons and high-contrast color matching are used to facilitate the driver to quickly identify and operate during driving [4].

4. Construction of the Evaluation System for Extreme Temperature Environments

4.1. Selection and Optimization of Evaluation Indicators

For extreme temperature environments, this study proposes a series of new evaluation indicators and optimizes existing indicators to more comprehensively and accurately evaluate the performance of automotive touch interaction systems [5].

Temperature sensitivity is one of the newly introduced key indicators, used to measure the sensitivity of touch interaction system performance to temperature changes. It can be determined by calculating the change rate of system performance indicators (such as response time and touch accuracy) under different temperature conditions [6]. For example, the formula for temperature sensitivity can be expressed as:

$$S = \frac{|p_2 - p_1|}{|T_2 - T_1|} \times 100\% \tag{1}$$

Where S is the temperature sensitivity, and P_1 and P_2 are the performance indicator values at temperatures T_1 and T_2 respectively. The lower the temperature sensitivity, the less the system performance is affected by temperature changes, and the higher the stability [7].

Temperature recovery time is also an important new indicator, which refers to the time required for the system to return to a normal working state after experiencing extreme temperatures. When a car moves from a high-temperature environment to a low-temperature environment, or from a low-temperature environment to a high-temperature environment, the system may experience performance degradation. Temperature recovery time can reflect the speed at which the system recovers normal performance after temperature changes, which is crucial for users who frequently use the car in different temperature environments. The shorter the recovery time, the stronger the adaptability of the system after temperature changes, and the shorter the time users wait for the system to return to normal operation, resulting in a better user experience.

Existing indicators such as response time and touch accuracy are also optimized to better reflect performance changes in extreme temperature environments. In high and low-temperature environments, the changes in response time and touch accuracy are often more complex. It is necessary to consider not only the average value but also the fluctuation range. Therefore, the standard deviation of response time and the standard deviation of touch accuracy are introduced to measure their stability. The formula for calculating the standard deviation of response time is:

$$\delta_{rt} = \sqrt{\frac{\sum_{i=1}^{n}\left(rt_i - \bar{rt}\right)^2}{n}} \tag{2}$$

Where δ_{rt} is the standard deviation of response time, rt_i is the response time of the i-th measurement, $\bar{rt}$ is the average response time, and n is the number of measurements. The calculation formula for the standard deviation of touch accuracy is similar. The smaller the standard deviation, the more stable the indicator, and the smaller the performance fluctuation of the system under extreme temperatures.

4.2. Design of Test Methods and Procedures

To comprehensively evaluate the performance of automotive touch interaction systems in extreme temperature environments, a series of targeted test methods and procedures are designed, including high-temperature tests, low-temperature tests, and temperature shock tests.

The high-temperature test aims to simulate the use of the car in a hot environment. The test equipment uses a high and low-temperature environmental chamber with precise temperature control, and the temperature range is set to 60°C - 80°C. This range is determined based on the temperature that may be reached inside the car when it is exposed to the sun for a long time in high-temperature weather in summer. The vehicle to be tested is placed in the environmental chamber to ensure it is in a normal working state, and relevant data collection equipment is connected to record various performance indicators of the system. During the test, the temperature in the environmental chamber is kept constant at the set value for a duration of 4 hours to simulate the car being in a high-temperature environment for a long time. Within these 4 hours, a performance test is conducted every 30 minutes, including the measurement of indicators such as response time, touch accuracy, and temperature sensitivity [8].

The low-temperature test simulates the use of the car in a cold environment. The temperature range of the environmental chamber is set to -40°C to -20°C, which is determined by referring to the extreme low temperatures in winter in northern China and the environmental temperatures that cars may face in extremely cold areas. The entire vehicle is placed in the environmental chamber for low-temperature pretreatment, allowing the system to stabilize in the low-temperature environment for a period of time, usually 1 hour, to ensure that all components of the system are fully adapted to the low-temperature environment. Then, performance tests are conducted. The test method is similar to that of the high-temperature test, with tests conducted every 30 minutes. The test indicators include response time, touch accuracy, temperature recovery time, etc. When testing the temperature recovery time, after completing the low-temperature performance test, the temperature of the environmental chamber is quickly increased to the normal working temperature (around 25°C), and the time required for the system to return to the normal working state (such as response time and touch accuracy returning to the normal range) after switching from the low-temperature environment to the normal temperature environment is recorded.

ISSN: 2688-8645

5. Experimental Verification and Data Analysis

5.1. Experimental Process and Data Collection

In the high-temperature test, the temperature of the high and low-temperature environmental chamber is set to 70°C. After the temperature stabilizes, this temperature is maintained for 4 hours. Within these 4 hours, every 30 minutes, the test subjects operate the touch interaction system in accordance with the operation task requirements. For example, during the click operation test, the test subjects need to click the navigation icon on the screen, and the test equipment records the response time from the moment the finger touches and leaves the screen to the moment the music interface pops up. During the sliding operation test, the test subjects need to slide from left to right on the screen, and the test equipment uses a laser displacement sensor to record the deviation between the actual position and the theoretical position of the touch point during the sliding process, so as to calculate the touch accuracy. At the same time, the test equipment monitors the operating state of the system in real-time and records software error information, such as memory leaks and code execution errors.

In the low-temperature test, the temperature of the environmental chamber is set to -30°C. Similarly, after the temperature stabilizes, this temperature is maintained for 1 hour to allow the system to fully adapt to the low-temperature environment. The test subjects perform operations in accordance with the same operation tasks as in the high-temperature test, and the test equipment collects the corresponding data. When testing the temperature recovery time, after completing the low-temperature performance test, the temperature of the test chamber is quickly increased to 25°C, and the time required for the system to return to the normal working state is recorded.

5.2. Data Analysis and Result Discussion

The collected data are processed using SPSS statistical analysis software. From the experimental results, in a high-temperature environment, the response times of the touch interaction systems of the three vehicle models are significantly prolonged. Among them, the average response time of the low-priced vehicle model increases from 800ms at normal temperature to 1200ms, with a standard deviation of 25ms; the mid-priced vehicle model increases from 700ms to 1000ms, with a standard deviation of 20ms; and the high-priced vehicle model increases from 650ms to 900ms, with a standard deviation of 15ms. Through variance analysis, it is found that high temperatures have a significant impact on the response times of the three vehicle models ($P<0.05$), which indicates that high-temperature environments significantly reduce the response speed of the touch interaction system, and the degree of impact varies among vehicle models of different prices, with low-priced vehicle models being more affected.

In terms of touch accuracy, all three vehicle models show varying degrees of decline at high temperatures. The touch accuracy of the low-priced vehicle model decreases from 95% at normal temperature to 75%, with a standard deviation of 8%; the mid-priced vehicle model decreases from 96% to 80%, with a standard deviation of 7%; and the high-priced vehicle model decreases from 98% to 85%, with a standard deviation of 6%. The results of variance analysis show that high temperatures also have a significant impact on touch accuracy ($P<0.05$), indicating that high temperatures reduce the ability of the touch screen to accurately identify the position of the touch point and affect the accuracy of user operations.

In a low-temperature environment, the touch interaction systems of the three vehicle models also show a trend of performance decline. In terms of temperature recovery time, the low-priced vehicle model takes an average of 8 minutes to return to the normal working state, the mid-priced vehicle model takes 6 minutes, and the high-priced vehicle model takes 4 minutes. Both response time and touch accuracy are affected to varying degrees. At low temperatures, the response time is prolonged and the touch accuracy is reduced, and the differences among different vehicle models are also significant ($P<0.05$).

Comprehensive analysis of the above experimental results shows that extreme temperatures have a significant impact on the performance of automotive touch interaction systems, and there are differences in the performance of touch interaction systems of vehicle models at different prices under extreme temperature environments. This is closely related to factors such as the hardware and software technology solutions adopted by the system and the quality of materials. The constructed evaluation system can effectively evaluate the performance of automotive touch interaction systems in extreme temperature environments. Through the testing and analysis of various indicators, the performance changes of the system under different temperature conditions can be fully understood, providing strong support for automobile manufacturers to improve product design and enhance the reliability of touch interaction systems.

6. Conclusion and Prospects

This study successfully constructs an evaluation system for automotive touch interaction performance in extreme temperature environments. Evaluation indicators are selected and optimized from multiple dimensions, including hardware performance, software performance, interaction experience, and reliability, covering key indicators such as temperature sensitivity, temperature recovery time, standard deviation of response time, and standard deviation of touch accuracy. These indicators fully reflect the performance of automotive touch interaction systems in extreme temperature environments. Targeted test methods and procedures, such as high-temperature tests, low-temperature tests, and temperature shock tests, are designed, and detailed evaluation standards are clarified, dividing the system performance into four levels: excellent, good, qualified, and unqualified, making the evaluation results intuitive and comparable.

Through experimental verification on touch interaction systems of three different brand vehicle models on the market, the effectiveness of this evaluation system is fully proven. The experimental results clearly reveal the significant impact of extreme temperatures on the performance of automotive touch interaction systems, and there are obvious differences in the performance of touch interaction systems of vehicle models at different prices under extreme temperatures. This provides strong data support and directional guidance for automobile manufacturers to improve product design and enhance the reliability of touch interaction systems. This evaluation system can help automobile manufacturers identify problems in a timely manner during the product development stage, optimize the design, improve product quality, and enhance market competitiveness. It also provides an important reference for consumers to purchase cars, enabling them to choose vehicle models with more stable performance in extreme temperature environments.

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