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Performance Testing and Analysis of Automotive-Grade CMOS Sensors in Different Environments

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Abstract: Automotive-grade Complementary Metal-Oxide-Semiconductor (CMOS) sensors play a crucial role in automotive electronic systems, especially in the context of the rapid development of Advanced Driver Assistance Systems (ADAS) and autonomous driving technologies. Their performance is directly related to the safety and reliability of vehicles. However, automobiles will face a variety of complex environmental conditions during the actual operation, such as high temperature, low temperature, vibration, humidity changes, and light changes, which may have an impact on the performance of CMOS sensors. Therefore, it is of great significance to study the performance of automotive-grade CMOS sensors in different environments.

Keywords: Automotive-grade CMOS sensor; Different environments; Performance testing

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1. Introduction

Vehicles experience a variety of environmental conditions in actual use, such as high temperature, low temperature, vibration, as well as changes in humidity and light, all of which may have an impact on the image quality and overall performance of the sensor. Therefore, studying the adaptability of automotive-grade CMOS sensors in various environments is of practical value for enhancing the stability and safety of automotive electronic systems. This paper aims to explore in depth the specific impact of different environments on the performance of CMOS sensors through systematic testing and analysis, to provide a reference basis for the optimal design and application of the sensors.

2. Overview of automotive-grade CMOS sensors

CMOS sensors capture and process images by converting optical signals into electrical signals. Its basic structure includes a photodiode, amplifier, analog-to-digital converter, and other components, and collaborates to complete the acquisition and output of image data. Compared with ordinary CMOS sensors, automotive-grade CMOS sensors have higher reliability and can operate stably in harsh environments, such as withstanding extreme temperature variations, vibration resistance, shock resistance, and many more. These characteristics make them widely used in the automotive industry [1].

3. Performance testing and analysis under a high-temperature environment

3.1. High-temperature environment simulation

To simulate the high-temperature conditions in actual use, sensors are usually placed in specific temperature environments, with the settings typically ranging from 85°C and 125°C, to test their working stability at extremely high temperatures. High temperatures may cause a series of problems, such as the increase in dark current, the increase in noise, and the decrease in image quality, all of which have a direct impact on the imaging performance of the sensor. The increase in dark current will lead to fixed-pattern noise in the image, while the increase in noise will blur the details of the image and reduce the overall sharpness. Simultaneously, high temperatures may also cause stress to the mechanical structure and electronic components of the sensor, affecting its long-term reliability [2].

3.2. Image quality test under a high-temperature environment

As the temperature rises, the dark current of the sensor increases, leading to an increase in noise, which in turn reduces the clarity of the image and blurs the details. The color reproduction ability will also be affected by high temperatures, resulting in color casts or reduced saturation, making the image colors no longer realistic. Additionally, the increase in noise level is a particularly prominent problem in a high-temperature environment. Both fixed mode noise and random noise will interfere with image quality, making the image appear with irregular bright spots or patches, affecting the visual effect [3].

3.3. Performance index test under a high-temperature environment

In high-temperature environments, the response time of the sensor may be slow, resulting in delays in capturing dynamic images and affecting real-time performance. Frame rate stability is also a key challenge in high-temperature environments. Excessive temperatures may cause the sensor to be unable to maintain a stable frame rate, resulting in jerky or incoherent images. Additionally, high temperatures can also lead to increased power consumption of CMOS sensors, which not only affects their energy efficiency performance but can also further exacerbate thermal management issues, posing a threat to overall system stability [4].

3.4. Performance analysis under a high-temperature environment

The dark current of the sensor increases at higher temperatures, leading to an increase in fixed pattern noise, blurring of image details, and loss of sharpness. At the same time, the color reproduction ability may be affected, resulting in color shift or lack of saturation. In terms of performance metrics, response time may slow down and frame rate stability may decrease, resulting in delays or inconsistencies in dynamic image capture. In addition, high temperatures can also cause power consumption to rise, further affecting the overall energy efficiency and thermal management of the sensor. These changes are primarily due to the impact of high temperatures on the physical properties of semiconductor materials and electronic components, making it difficult for sensors to maintain stable performance outputs under extreme conditions [5].

4. Performance testing and analysis in a low-temperature environment

4.1. Low-temperature environment simulation

Performance testing in low-temperature environments needs to be carried out under tightly controlled conditions, usually with the temperature set at −40°C or even lower to simulate the working conditions of the vehicle in extremely cold climates. The setting of low-temperature test conditions not only includes the temperature itself but also involves the comprehensive regulation of humidity, air pressure, and other factors to ensure that the experimental environment is as close as possible to the actual working conditions. At low temperatures, the semiconductor characteristics of CMOS sensors change, resulting in longer response times, lower frame rates, and increased power consumption. Moreover, low temperatures will also degrade the performance of liquid crystal materials and electronic components in the sensor, resulting in a deterioration of image quality, such as increased noise and color distortion [6].

4.2. Image quality test in a low-temperature environment

As the temperature decreases, image clarity may decline, mainly in the form of blurred details and unclear edges, due to slower sensor response and reduced performance of electronic components. Color reproduction is also affected at low temperatures, with color casts and lack of saturation more common, resulting in distorted colors and an inability to accurately represent the true colors of the scene being captured. Furthermore, low temperatures will also lead to an increase in noise levels, particularly fixed pattern noise and random noise, further degrading image quality, with details becoming unclear and distracting [7].

4.3. Performance index test under a low-temperature environment

At low temperatures, the response time of automotive-grade CMOS sensors tends to be longer, mainly due to a decrease in carrier mobility of semiconductor materials, resulting in slower signal processing. Frame rate stability is also affected, and low temperatures may cause frame rate fluctuations or drops, especially in high dynamic range scenes, where frame-to-frame coherence deteriorates and the ability to capture dynamic images is diminished. Additionally, low temperatures will also lead to increased sensor power consumption due to increased circuit impedance, which reduces the efficiency of current transfer and requires more power to maintain normal operation [8].

4.4. Performance analysis in a low-temperature environment

Low temperatures lead to reduced photoelectric conversion efficiency, resulting in reduced image clarity, poor color reproduction ability, color shift, and insufficient saturation. Concurrently, low temperature also triggers an increase in noise levels, especially fixed pattern noise and random noise, further affecting the image detail performance. In terms of performance metrics, the problem of extended response times and unstable frame rates are particularly prominent, which are closely related to the decrease in semiconductor carrier mobility and the increase in circuit delays. The rise in power consumption is due to the increase in circuit impedance at low temperatures, which causes the system to consume more power to maintain normal operation [9].

5. Performance testing and analysis under vibration environment

5.1. Vibration environment simulation

In general, vibration tests are performed at different frequencies and accelerations to simulate the various vibration conditions that a vehicle may encounter during actual road driving, including smooth and bumpy road surfaces. The influence of vibration on the sensor is mainly reflected in both mechanical structures and electronic components. Mechanical vibration may lead to minor displacement or poor contact with the internal components of the sensor, which in turn affects the imaging stability, resulting in blurred image jitter, and other problems. Electronic components may experience unstable signal transmission under continuous vibration, resulting in increased image noise or frame rate fluctuations. Theoretically, the higher the vibration frequency and the greater the acceleration, the more pronounced the negative impact on the sensor.

5.2. Image quality test under vibration environment

In the vibration environment, the image quality of automotive-grade CMOS sensors will be significantly affected. Firstly, the image clarity tends to deteriorate, and vibration-induced mechanical displacements can lead to poor focusing or image shaking, resulting in blurred images. The loss of detail at the edges of the image is particularly noticeable under high-frequency vibration conditions. Secondly, the color reproduction ability will also be affected, and the vibration may lead to the instability of the sensor's internal color processing circuit, resulting in color deviations and a lack of saturation in the image. Moreover, noise levels rise significantly in vibration environments. Mechanical vibration exacerbates interference in the internal circuitry of the sensor, leading to an increase in fixed patterns and random noise, further affecting the overall quality of the image [10].

5.3. Performance index test under vibration environment

Vibration may cause the delay of the sensor's internal circuit to increase, which makes the response time of image capture longer and affects the real-time imaging effect. At the same time, the stability of the frame rate is susceptible to interference under vibration conditions, especially under severe vibration, the sensor may have frame loss or frame rate fluctuations, resulting in incoherent or jerky images. Furthermore, vibration can lead to increased power consumption due to unstable contact between components in the circuitry and the additional mechanical stresses caused by vibration, which require more power to maintain normal operation [11].

5.4. Performance analysis under vibration environment

In the vibration environment, the reason for the degradation of the image quality in automotive-grade CMOS sensors is mainly related to the inaccurate focusing and small displacement of the internal components triggered by mechanical vibration which will lead to the phenomenon of blur and jitter in the imaging process. Meanwhile, vibration also affects the optical system of the sensor, causing the light entering the sensor to shift, further affecting the clarity of the image and color reproduction ability. Vibration-induced circuit instability increases response time and affects the data processing speed, while the fluctuation of frame rate is associated with the sensor's difficulty in maintaining a stable image output under vibration conditions. The increase in power consumption is due to the extra energy consumption in the circuit to cope with vibration-induced disturbances and mechanical stress [12].

6. Performance testing and analysis in a humidity-varying environment

6.1. Environmental simulation of humidity change

Multiple humidity test conditions, covering a wide range from low to high humidity, are usually set to simulate the variety of environments that may be encountered during actual driving. The influence of humidity change on the sensor is mainly reflected in two aspects. On the one hand, high humidity may lead to condensation on the internal circuitry or the surface of the optical components of the sensor, which affects the normal transmission and reception of light, resulting in a decline in image quality. On the other hand, the fluctuation in humidity may also cause the risk of leakage of electrical current or short circuits in the circuitry, which affects the stability and lifespan of the sensor [13].

6.2. Image quality test under humidity change environment

The image quality of automotive-grade CMOS sensors can be significantly impacted under changing humidity environments in several ways. Firstly, image clarity decreases with the increase of humidity, mainly because the moisture may form condensation droplets on the surface of the sensor optical elements, causing light scattering, which in turn triggers image blurring. Secondly, the color reproduction ability is also affected by humidity. A high humidity environment may lead to color distortion or saturation decline, making the imaging effect deviate from the real scene [14].

6.3. Performance index test under humidity change environment

Response times tend to get longer when humidity increases, mainly because moisture may trigger delayed or unstable signal transmission in the circuitry. Frame rate stability is also affected by humidity fluctuations. In high-humidity environments, changes in the electrical characteristics of the sensor's internal components may cause frame rate drops or irregular fluctuations, affecting the continuity and fluency of the image. Additionally, power consumption generally increases in humid environments because the circuitry requires additional energy to cope with the risk of moisture-induced current leakage or short circuits. Test results show that humidity changes have brought challenges to sensor responsiveness, frame rate consistency, and power consumption management and that the degradation of these performance metrics is especially pronounced in extreme humidity conditions [15].

6.4. Performance analysis under humidity change environment

Increased humidity can cause water vapor to condense on the sensor lens or protective glass, interfering with the normal transmission of light, and resulting in blurred images, reduced contrast, and color distortion. Also, moisture penetration into the sensor interior may cause trigger circuit failure or signal interference, further affecting the imaging effect. In terms of performance indicators, the extension of response time and the instability of frame rate are usually related to humidity-induced circuit signal delays and changes in electrical characteristics. In parallel, the increase in power consumption is due to the extra energy required by the circuitry to cope with the risk of moisture-induced current leakage or short circuits. These changes indicate that humidity has a significant impact on both the optical and electrical performance of sensors, especially in high-humidity environments, where sensors require stronger environmental adaptability to maintain stable image quality and reliable performance output [16].

7. Performance testing and analysis in light-varying environments

7.1. Simulation of light-variable environments

For testing in light-varying environments, light conditions for automotive-grade CMOS sensors are typically set to cover a wide range of scenarios from low to high brightness, including nighttime, tunnel, daytime, and bright light environments. These test conditions are designed to simulate various lighting conditions that the sensor may encounter in real-world applications. Theoretical analysis shows that the influence of light variations on CMOS sensors is mainly reflected in image quality and dynamic range. In low-light environments, the sensor may experience problems with increased image noise and loss of detail, resulting in blurred imaging. However, under the conditions of high brightness or strong direct light, the sensor is prone to overexposure, resulting in image details being covered by excessively bright light. On top of that, rapid light variations may also trigger a lag in the sensor's automatic exposure adjustment, affecting the continuity and stability of the image [17].

7.2. Image quality testing under light-varying environment

Image sharpness tends to decrease significantly in low light conditions, with details becoming blurred, mainly due to the lack of sensor sensitivity, resulting in less sharp images. In bright environments, excessive light may cause overexposure of the image, which also causes loss of clarity. Color reproduction ability also shows differences in different lighting conditions, with colors easily darkened or distorted in low light, while over-saturated colors may occur in strong light. Noise levels increase significantly in low-light environments, with more graininess appearing in the image, affecting the overall visual effect, due to the need to increase the gain of the sensor in low light, resulting in increased noise [18].

7.3. Performance index testing under light-varying environment

In the light-varying environment, the response time of automotive-grade CMOS sensor may be different under different lighting conditions, especially when the light intensity changes rapidly, the length of time for the sensor to automatically adjust the exposure directly affects the timeliness of the imaging. Frame rate stability is also affected by changes in illumination, and in low-light environments to increase the amount of incoming light, the sensor may reduce the frame rate, resulting in a decrease in the continuity of image capture. In bright environments, too fast exposure adjustment may cause frame rate instability, resulting in image jitter or stutter. In terms of power consumption changes, low-light environments typically require sensors to increase their gain to enhance image brightness, which leads to increased power consumption. In contrast, in normal or bright environments, the power consumption is relatively low [19].

7.4. Performance analysis under light-varying environment

Under low-light conditions, the sensor usually boosts the gain to increase the amount of incoming light, which easily leads to increased image noise and blurred details. In brighter environments, excessive light may cause overexposure, resulting in loss of image detail and color distortion. Additionally, when the lighting changes rapidly, the sensor's automatic exposure adjustment, if not quick enough, may cause images to be briefly blurred or have color deviations. The analysis of the change of performance indicators shows that the response time and frame rate may fluctuate when the lighting changes dramatically, mainly because the sensor needs time to adapt to the new lighting conditions, especially in the transition stage from low light to strong light or from strong light to low light, where the frame rate drop and response delay are more obvious. In terms of power consumption, the high-gain mode in a low-light environment will increase the power consumption, while the power consumption in a bright environment is relatively low [20].

8. Conclusion

Tests in different environments show significant differences in the performance of the automotive-grade CMOS sensors, covering a variety of conditions such as light variations, temperature fluctuations, and complex road conditions. Sensor image quality, frame rate stability, and power consumption are all affected to varying degrees in different environments, and performance fluctuations are more pronounced under extreme lighting and temperature conditions. Adaptive design, such as automatic exposure adjustment, enhanced noise reduction algorithms and optimized power consumption management, can effectively improve the performance of CMOS sensors in various environments.

Disclosure statement

The author declares no conflict of interest.

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