https://doi.org/10.2352/EI.2024.36.17.AVM-110

An integrated and fully automated test solution for automotive cameras of ultrawide angle of view

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Abstract

Vehicle-borne cameras vary greatly in imaging properties, e.g., angle of view, working distance and pixel count, to meet the diverse requirements of various applications. In addition, auto parts must tolerate dramatic variations in ambient temperature. These pose considerable challenges to the automotive industry when it comes to the evaluation of automotive cameras in terms of imaging performance. In this paper, an integrated and fully automated system, developed specifically to address these issues, is described. The key components include a collimator unit incorporating a LED light source and a transmissive test target, a mechanical structure that holds and moves the collimator and the camera under test, and a software suite that communicates with the controllers and computes the images captured by the camera. With the multifunctional system, imaging performance of cameras can be conveniently measured at a high degree of accuracy, precision and compatibility. The results are consistent with those obtained from tests conducted with conventional methods. Preliminary results demonstrate the potential of the system in terms of functionality and flexibility with continuing development.

Introduction

In recent years, road vehicles have been equipped with an increasing number of cameras, for driver assistance, driver and occupant monitoring, rear view, around view monitoring, etc. Such vehicle-borne cameras differ greatly in imaging parameters to suit the specific requirements of a certain application. For instance, cameras designed for driver assistance may be focused on distant objects, whereas the objects at which driver and occupant monitoring systems are aimed may be merely centimeters away. Similarly, around view cameras often possess an ultrawide angle of view (hereafter abbreviated to AoV), while the AoV may be rather narrow for cameras detecting objects at considerable distances.

Conventional objective imaging performance tests of digital cameras, e.g., those for photographic use, are often conducted in a lab where one takes photos of certain properly illuminated test targets with the camera under test and then analyze the images with dedicated software to obtain the results. In practice, a long working distance entails a large space that often turns out to be inaccessible to the testers. Moreover, the test targets are geometric patterns usually formed on a planar surface made of paper, metal, or photographic film. At a given working distance, the wider the camera’s AoV is, the larger the test target would be in size. Even if a large and bulky test target is acceptable, the angular field of view of a camera cannot be entirely covered by a planar target when it equals and exceeds 180 degrees.

In the development of vehicle-borne cameras, there is often a need for an automated image quality testing solution of high accuracy, high precision, high compatibility, and compactness. The issues mentioned above, however, pose considerable challenges of image quality assessment to the automotive industry.

Moreover, dramatic variations in ambient temperature that automotive cameras must withstand result in thermal expansion of the camera hardware, which may in turn degrade the resultant image quality. This necessitates the acceptance testing where the image quality ought to be measured across the operating temperature, which further complicates the design of such a test system.

To address these issues, we have developed an integrated and fully automated system, which makes feasible multi-functional testing of a wide variety of automotive cameras. It supports major test items, e.g., the e-SFR (edge-based spatial frequency response), through-focus e-SFR, geometric distortion, AoV, etc., at a high degree of accuracy and precision.

In the subsequent sections of the paper, we will introduce how each problem is resolved and describe the system in detail. Some of the validation results will be shown, with reference to those obtained with conventional methods.

Collimator with adjustable focus: a solution to the varying working distance

As is known, a virtual image is formed at a distance when the object is nearer to a magnifying glass than the focal point on the same side. First-order optics implies that an object and its image obtained through a lens are conjugate to each other. An optical collimator is essentially a lens or a mirror, and it by definition has the object located at the focal plane and its image at infinity. Therefore, a collimator designed with adjustable focus in mind, i.e., the object distance may be varied, gives rise to distant virtual images of high quality at a range of image distances. The virtual image formed by a collimator becomes a real object for the camera under test.

For ease of use, the collimator is integrated into a compact package with painstaking calibration. The package consists of a light source, a test target, an actuator as well as other mechanical parts, in addition to the collimator. The transmissive test target is attached to a circular light source through a substrate made of glass, which, driven by the actuator, moves bidirectionally along the optical axis of the collimator to simulate the desired object distances. The light source illuminates the test target uniformly through a diffuser, underneath which lies an LED array that emits light resembling the CIE D65 daylight illuminant in terms of the spectral power distribution.

The core idea behind the use of a collimator with adjustable focus is to make the system compatible with varying object distances, required by a wide range of automotive cameras, without taking up much space. The adjustability of focus also makes possible so-called through-focus scanning where an image quality test is conducted across a range of object distances. A good example is the through-focus e-SFR measurement that will be explained in detail in a subsequent section.

In the reference design, the collimator can produce a range of working distances from 0.4 meter all the way to infinity and subtends an angular field of view of 15 degrees.

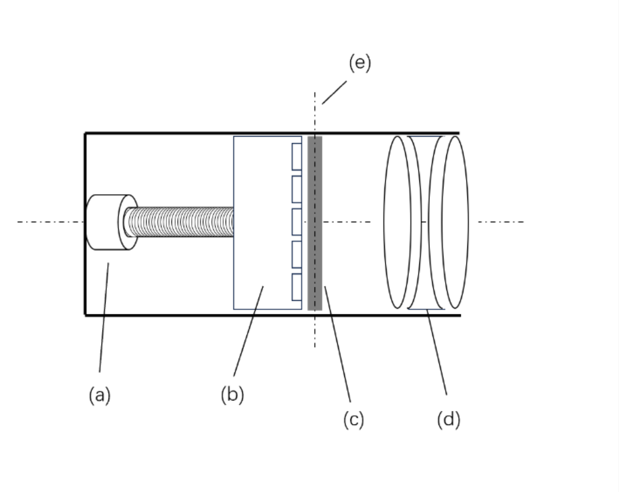

***Figure 1**. An illustration of the collimator package and its components: (a) actuator and leadscrew, (b) uniform LED light source and controller, (c) transmissive test target, (d) collimating lens, (e) front focal plane of the collimator lens*

Goniophotometer-like structure: a solution to the varying angle of view

A goniophotometer, used for angular photometric measurements of a light source, usually contains a measuring instrument that rotates about the light source in question located at the centre of rotation. In our design akin to the goniophotometer, the collimator package rotates about the camera under test to measure image quality of the camera at different locations on the image plane.

In geometric optics, the entrance pupil of an objective refers to the image, often virtual, of the aperture stop in the object space. In fact, we could not see the iris in others' eyes itself but only its image formed by the cornea. For this reason, the pupil we observe is the entrance pupil of the eye. For an imaging lens, any ray that would pass through the centre of its entrance pupil, if it were not refracted, passes through the centre of its aperture stop, because of the conjugate relationship between the two. And the ray that emanates from a point in the object space and passes through the centre of the entrance pupil is known as the chief ray of the image-forming pencil. At a given working distance, all chief rays in the object space intersect at the centre of the aperture stop and that of its entrance pupil accordingly. Here the centre of the entrance pupil also serves as the no-parallax point.

For cameras of ultra-wide AoV, e.g., those with a fish-eye lens, however, there exists no single entrance pupil, since no light would enter the lens at an angle no less than 90 degrees to the optical axis if the entrance pupil were in a fixed plane perpendicular to the axis [1]. As a matter of fact, the entrance pupil moves forward, sideways and tilts over toward the incoming light as the obliquity is increased. The most appropriate centre of rotation would therefore be a close estimate of the ideal no-parallax point.

As a result, the collimator package rotates about the no-parallax point in a tangential plane of the lens of the camera under test to cover the test across the AoV. In addition, the camera under test should rotate about the optical axis of the lens to allow the test target to appear at any azimuthal angle. Also, the collimator package ought to rotate about its optical axis to compensate for the rotation of the camera, so that the orientation of the test target would remain constant in the resulting digital image.

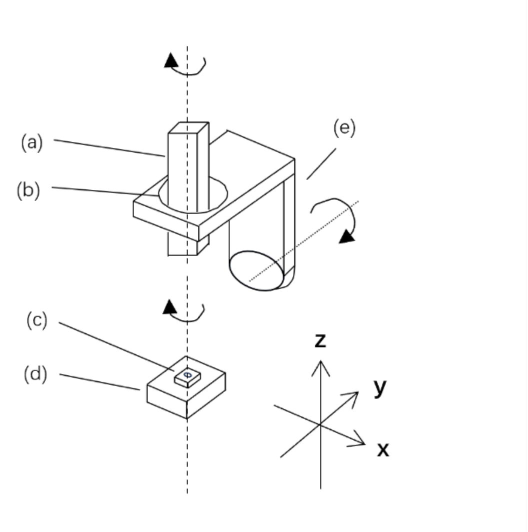

***Figure 2**. An illustration of key system components: (a) collimator package, (b) motorized rotary stage, (c) camera under test, (d) 6-axis platform, (e) rotary arm*

System design on a modular basis

The individual components mentioned above are integrated into a standalone system encased in a metallic cover with the inner and outer surfaces in black matte finish to reduce reflections. The hardware system consists mainly of a rotary arm and a platform having 6 degrees of freedom. The collimator package is attached to the former through a rotary stage, while the latter holds the camera under test.

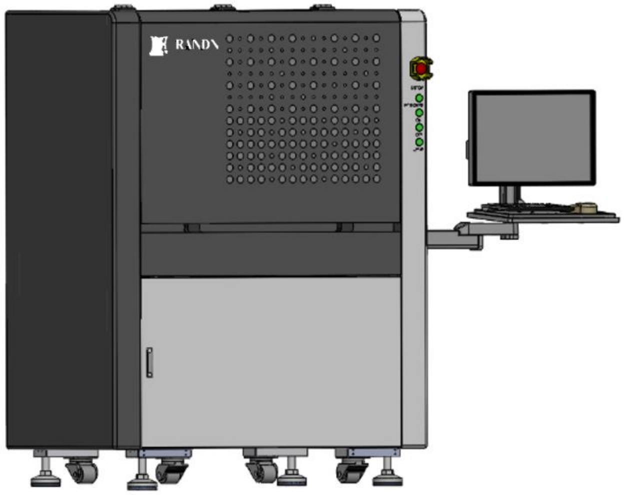

***Figure 3**. An illustration of the exterior of the system*

The arm rotates about a centre, supposedly the no-parallax point of the camera, and the stage allows the rotation of the collimator about its own optical axis. In the reference design, the rotation of the arm covers a range of 210 degrees. The platform enables translation and rotation of the camera to ensure that the collimator and the camera are coaxial, the distance between the collimator and the camera is appropriate, and the no-parallax point coincides with the centre of rotation.

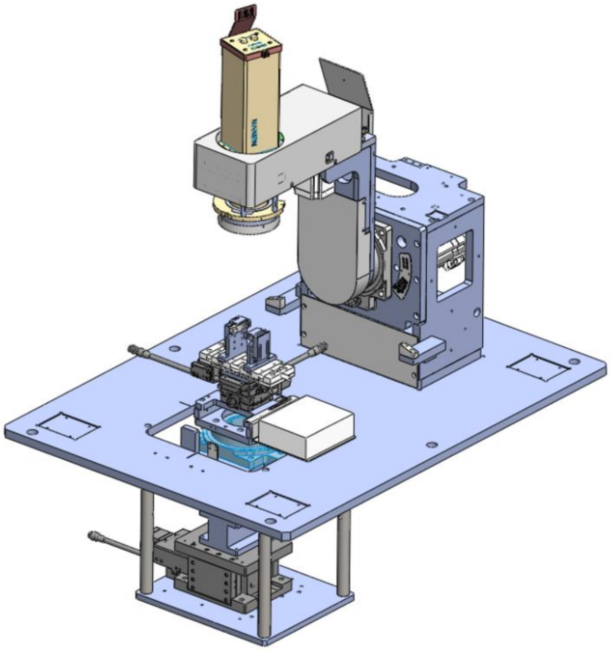

Figure 4*. An illustration of the mechanical structure of the system*

Both the hardware and the software of the system were designed on a modular basis. In consequence, the system is highly flexible and adaptable. For instance, the test target and the image analysis module may be replaced to support new test items. An example will be shown in the two subsequent sections.

Multiple-functional testing enabled by a unique test target design

It is expected that the system is capable of multiple test items, including, but not limited to, the e-SFR in accordance with the ISO 12233 standard [2].

The computation of the e-SFR relies on a slanted edge in the test target. In practice, the diversity of cameras in terms of pixel count and AoV result in varying instantaneous field of view (i.e., the AoV covered by a single pixel), so that the number of pixels that the test target occupies in the digital image varies greatly. This may lead to failure of e-SFR computation due to edges of insufficient length, or inaccurate results due to excessively large target image. To that end, a new pattern was created, which comprises two concentric squares both tilted at a slight angle. It is consistent with the ISO 12233 standard and meets the needs of a wider range of instantaneous field of view.

Further the adjustability of focus of the collimator allows the so-called through-focus e-SFR test. In such a test, the e-SFR test is conducted against a range of object distances. The highest performance is delivered when the camera under test is focused on the virtual test target produced by the collimator. When the test target shifts from the optimal focus position, the resulting image becomes blurred due to poorer performance. The results of a through-focus e-SFR test is often seen as a complete or partial Gaussian function shaped curve with its peak indicating the best focus position. Through-focus e-SFR test may help to determine if the optimal object distance of a camera in practice is consistent with the specification, which is an indicator of manufacture quality. Such a scan also assists in measuring the effective depth of field, given a criterion, e.g., for the lower limit of resolution that the object detection algorithms accept.

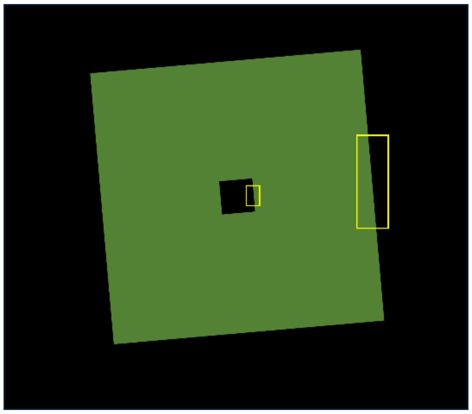

Figure 5*. An illustration of the double-square test pattern. The bounding boxes in yellow indicate the region of interest for the computation of the edge spread function and eSFR.*

In addition to the e-SFR, the hardware configuration enables other test items as well. Probably the most obvious one would be the angle of view, as the rotation of the arm allows the radial movement of the test target towards the corners until it disappears from the view. In this process, geometric distortion may also be conducted, as both the chief ray angle, i.e., the angle of rotation of the arm, and the corresponding field positions are known. Another test supported is lateral chromatic aberration that measures the displacement of the edge spread function across the trichromatic channels.

Thermal testing capability

Considering the dramatic variations in ambient temperatures road vehicles shall withstand, deformation of the camera structure and components due to thermal expansion may introduce defocus. To that end, a temperature chamber may be integrated into the design so that the camera under test is placed in the chamber.

At each temperature, a through-focus e-SFR test yields a bell-shaped curve with a peak. Variations in temperature often cause the peak to shift in terms of object distance. Thermal tests may help the developers and users of automotive cameras to better understand and verify the degradation of image quality and recognition rate due to ambient temperature variations.

Furthermore, a nondestructive inspection of the temperature drift in the back focal length of cameras is thus made feasible, as image distance and objective distance are related by focal length. For this purpose, collimator packages with extended range of object distances might be useful to ease the location of the peaks in the bell-shaped curve and in turn facilitate determining the thermal drift. A replacement of the collimator package is straightforward thanks to the modular design of the system.

In a reference design, the chamber has a temperature range from a minimum around -40℃ to a maximum around 125℃.

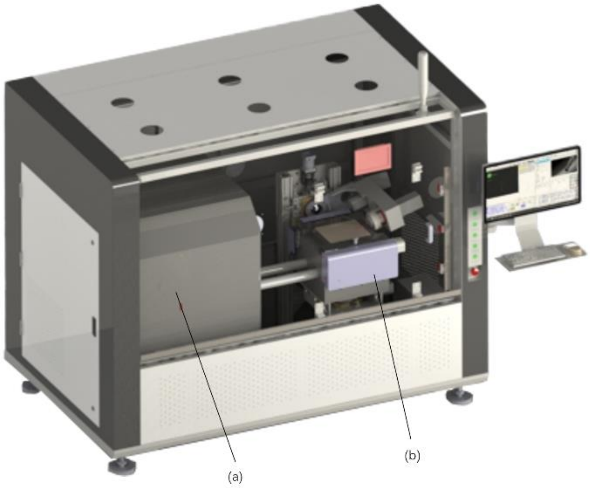

***Figure 6**. An illustration of the extended system that supports thermal testing. (a) air conditioner, (b) temperature chamber*

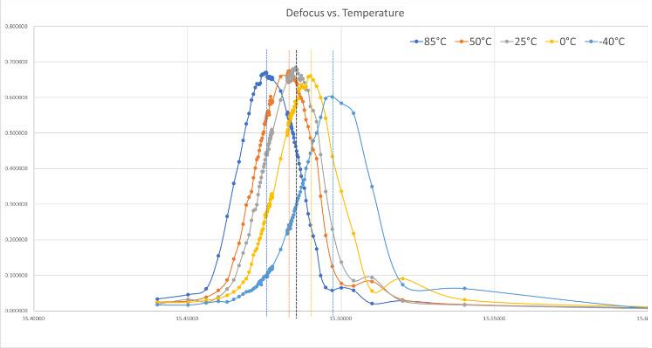

***Figure 7**. The through-focus e-SFR curves showing the thermal drift of back focal length*

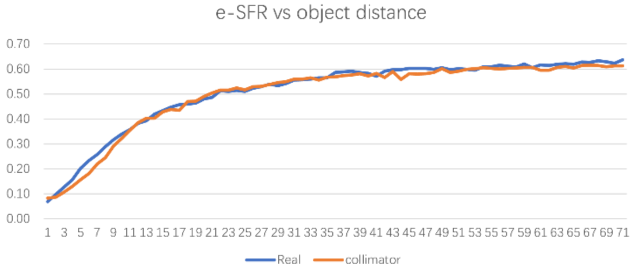

***Figure 8**. The e-SFR test results obtained from test target images captured using the same camera across a range of object distances with a collimator and in reality respectively*

Validation and results

Without doubt the e-SFR is the most important function of this system, and the key component that differentiates this system with conventional lab tests is perhaps the collimator. Systematic and thorough validations then became necessary. As a starting point, we first evaluated the ISO 12233 complaint image analysis module, that computes the e-SFR from a test image. We fed the same set of test images to the module developed in-house and another industrially recognized camera image quality analysis tool, and the results show great consistency. Further, we used a camera to capture images of the test targets across a range of object distances with the collimator and at the same physical distances respectively. The results show that the results obtained with the collimator are very close to those obtained with printed test charts placed at the same object distances up in reality.

Conclusions

Overall, the system meets our expectations as an automated solution for ultrawide AoV camera testing of high accuracy, high precision, high compatibility and compactness. The system supports multiple test items, such as e-SFR, through-focus e-SFR, AoV, geometric distortion, chromatic aberration. It is also feasible to introduce thermal testing into the design.

The modular design of the system enables expandability and upgradability. Preliminary results demonstrate the clear advantage of the circle-shaped test pattern, such as the capability of measuring omnidirectional e-SFR, the resistance to geometric distortion, the robustness in measuring chromatic aberration, the potential for assessing veiling glare, to name but a few.

References

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[2] Photography - Electronic still picture imaging - Resolution and spatial frequency responses, ISO 12233:2023, International Organization for Standardization, Geneva, Switzerland, Feb. 2023.

Author Biography

Xingbo Wang received his MSc in color in informatics and media technology from the Erasmus Mundus master programme of the same name (2011) and his PhD in computer science from the Norwegian University of Science and Technology (2016). He showed a keen interest in the fundamentals of cameras from his childhood. A member of SMPTE, he has worked on imaging performance analysis of cameras for videographic, photographic and automotive use.

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