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The influence of image capture and processing on MTF for end of line test and validation

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Abstract

Slanted edge MTF measurement as per ISO12233 is the de facto standard for measuring camera sharpness at manufacturing end of line. MTF measured by slanted edge has a number of advantages for measuring sharpness, being scale invariant, and relatively robust to geometric distortion. However, slanted edge MTF measurement is known to be affected by image processing algorithms, including demosaic, edge enhancement, and denoise algorithms. To avoid these confounding factors, it is increasingly common to measure MTF directly from the raw sensor image. This approach is logical if you are assessing the optomechanical lens-imager alignment and focus. However, end-of-line production testing has specific requirements, including speed of execution, repeatability and reproducibility. These requirements are typically not considered when configuring a camera for end-of-line MTF measurement. In this study, the execution time, repeatability and reproducibility of MTF measurement for multiple image capture and image processing combinations are examined.

Introduction

Automotive camera systems face significant challenges when it comes to mass production. To enable autonomous driving and Advanced Driver Assistance Systems (ADAS), automotive cameras have significantly higher performance requirements in many aspects, especially when compared with consumer electronic camera systems. Requirements around low light performance, High Dynamic Range (HDR), resolution, flare etc. have necessitated the development of the P2020 Automotive Image Quality Standard [1] (pre-release published in 2022).

An additional challenge is that automotive cameras are fixed focus. This is because state of the art auto-focus mechanisms cannot survive the mechanical and thermal robustness requirements for automotive applications. This presents significant challenges for automotive camera manufacturing. To illustrate this, consider an example of an automotive camera system where the image sensor pixel pitch is 2µm, and the lens has an f number of 1.6 and a track length of 15mm. In this example, the depth of focus can be $<$20µm.

Modulation Transfer Function(MTF)

MTF measured using the slanted edge method defined in ISO 12233 [2], is commonly used in the camera manufacture process. The slanted edge methodology has a number of advantages over other methods (e.g. Sinusoidal Siemen's Star targets or dead leaves targets) in the manufacturing setting; slanted edge measurements are easier to automate, are more efficient in terms of space usage, can measure MTF above the Nyquist limit, and are more robust against geometric distortion. ISO 12233 provides guidelines for camera configuration, with the goal of improving measurement accuracy. These include linearizing the camera image i.e. inverting the opto-electronic conversion function (OECF), preventing overexposure, and ensuring the edge angle is within the recommended range [2]. The recommended chart design has also been updated in the 2017. Updates include a simplified design to facilitate automated measurement, and a lower contrast ratio to prevent measurement errors due to clipping. While these changes have all been highly beneficial, there remain several open questions regarding camera configuration and image processing, and their impact on MTF measurements, particularly in the context of high volume camera manufacturing.

Image processing and MTF measurements

It is widely known and understood that image processing heavily influence MTF measurements. Slanted edge meaurements in particular are known to be highly impacted by edge enhancement algorithms. Denoise algorithms and tone mapping are also known to have an impact. Indeed, as previously mentioned, ISO 12233 recommends inverting the OECF, as non-linear tone mapping is known to impact measurements. However, in many cases (e.g. local tone mapping algorithms), the OECF is dynamically generated based on spatially local statistics in the image. It is not possible to invert the OECF used. It is therefore often recommend to minimize the image processing applied when measuring MTF with slanted edge targets.

Image Demosaic

A lesser discussed but critical aspect of image processing is the demosaicing process used to convert raw sensor data into colour image data. A full description of demosaic algorithms is beyond the scope of this work. Briefly, the vast majority of digital image sensors capture one colour per pixel. Demosaic algorithms then use interpolation techniques to reconstruct three colours per pixel, typically red, green and blue for standard colour images. A more detailed survey of demosaicing approaches is detailed in the following works [8, 3, 9, 4].

While some studies have reviewed slanted edge variability [11, 12], and interactions between demosaic algorithms and MTF measurements [10], the authors are unaware of any studies which have systematically examined the impact of image demosaicing on MTF measurements, particularly in the context of high volume camera manufacture. In the next section, the specific challenges MTF measurement for camera mass production are discussed.

Camera Mass Production

Broadly speaking, MTF is critical for two phases of camera manufacture: lens-imager alignment and end of line validation. As mentioned previously, automotive cameras are fixed focus cameras with no autofocus mechanism. The lens must therefore be aligned relative to the image sensor and fixed in position at the point of optimal focus during the camera assembly process. Once the lens and image sensor positions are fixed at the point of best focus, an end of line focus validation test is also performed, to ensure the camera meets the resolution requirements demanded of the customer and/or application.

In the context of the manufacturing process, the capability of the measurement process is critical. In any company, significant effort is expended to reduce process variation, defect rates and improve cycle time. There are many approaches to performing this task, with Six Sigma being a well known example. A full description of manufacturing quality control and process optimization are beyond the scope of this work. Briefly, a key priority of quality control and process optimization is to reduce the variability of the measurement process itself. An illustrative example of this is shown in Figure 1. In this example, MTF50 measurements for a build of 200 cameras is shown, and the pass/fail limit is indicated by the dashed line. Parts with measured MTF50 above the limit are considered ”good” parts, and are shipped to the customer. Parts below the limit are considered ”bad” parts. Typically, automotive cameras do not go through a re-work process. As a result, ”bad” parts are typically scrapped. In this example build, the majority of parts exceed the pass/fail limit comfortably. Three parts, indicated in red, clearly fall below the limit, and are scrapped. However, one part, marked in green, is marginally above the pass/fail limit. However, if the process variability is high (i.e. if there is significant variability in the measurement process itself), then this part may randomly pass or fail the production MTF50 limit. This is obviously a concern for camera manufacturers; to maintain profitability, scrapped parts must be kept to an absolute minimum, and failing parts due to measurement variability is clearly unacceptable.

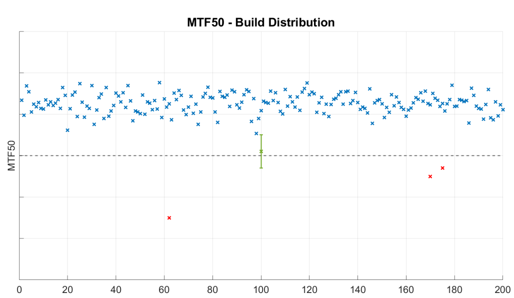

Figure 1. *Exemplory distribution of camera MTF50 measurements at end of line testing. Pass/fail limit is indicated by the dashed line*

From this perspective, the slanted edge measurement process presents multiple issues for camera manufacturers. Previous work in the literature has demonstrated the slanted edge MTF measurements are highly affected by image processing [14, 15, 16]. For this reason, image processing is generally minimized, particularly for end of line pass/fail testing - with sufficient edge enhancement applied, practically any camera, no matter how poorly focused, could be made to pass any end of line MTF limit.

Previous work has also illustrated that slanted edge MTF measurements also exhibit relatively high levels of measurement variability, even in ideal circumstances [11, 12, 13]. Despite these shortcomings, the slanted edge methodology remains popular, because of its efficient use of space and ease of automation.

In this study the authors examine the impact of image processing on MTF measurements, specifically for high volume camera manufacture process. In particular, the impact of choice of image demosaic algorithms on MTF measurement variability is explored.

Methods

Camera through-focus test

As mentioned previously, MTF measurements are used to identify the position of optimal focus during lens-imager alignment. To assess the impact of image processing on this task, the authors performed a through focus sweep. The test setup used is shown in Figure 2. A camera was placed on a tripod 30cm from an ISO 12233:2017 compliant test target (Imatest eSFR target). The camera used was a Blackgly BFS-U3-89s6M camera, with a Sony IMX255 image sensor. The lens F# used was 2.0. The target was illuminated by 2 LED panels with a CCT of 5000K, and an illumination of 500lx at the target. To minimize the impact of image noise, the exposure time was set to 32ms, and the sensor gain was set to 0dB. The images were white balanced, with the gains applied at the image sensor. A focus ring was connected to a servo motor controlled by an Arduino. Images were taken at a total of 80 steps through the entire focus range of the camera. At each focus step, 30 raw images were captured for analysis.

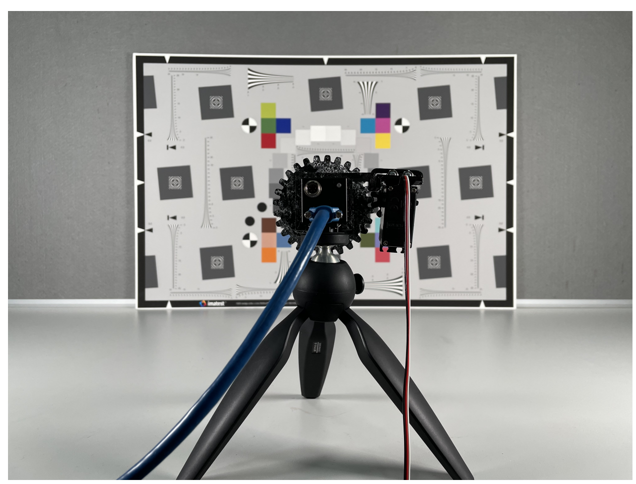

Figure 2. *Test setup for through focus sweep.*

Image Processing

The raw sensor images were converted to RGB images using a variety of demosaic algorithms, using a combination of MATLAB scripts. This included the default MATLAB demosaic algorithm by Malvar et al [3], as well as nearest neighbor, bilinear, smooth hue, and gradient demosaic algorithms, implemented by Jonathan Lin [4]. In these use cases, no other image processing was applied after demosaic. Additionally, raw green pixel data (Gb channel), and a fully ISP processed images were also analysed. The ISP used was fastopenISP, developed by Qiu Jueqin [17]. A default configuration with Malvar demosaic, unsharp mask edge enhancement, bilateral noise filtering and gamma correction was used. This was a typical ISP configuration used for image display - no specific tuning for manufacturing was performed.

Data analysis

MTF was calculated using sfrmat4.m, the standard reference slanted edge MTF measurement implementation [18]. MTF50 was chosen as the metric for this study, as it generally correlates well with perception of sharpness [14]. In total, MTF50 was measured from six slanted edges, as shown in Figure 4.

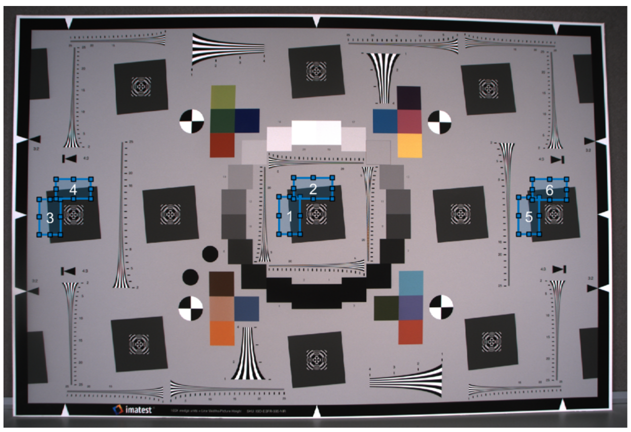

Figure 3. *Edges used for MTF50 analysis.*

For each focus step, the mean and variance of the 30 captured images were measured. From this, the coefficient of variation was also measured (i.e. σ/μ). To assess measurement system capability, a Gauge R&R ANOVA analysis was also performed. This included analysis of the number of discrete categories (NDC) and total %GRR. The Automotive Industry Action Group (AIAG) recommendations [19] for Gauge R&R are included in Table 1. Essentially, a higher number NDC means that the measurement system is capable of distinguishing the data into more categories (e.g. if NDC=2, then the measurement system can only reliably classify parts into two categories, high and low), and %GRR indicates how much of the total variation in the data can be attributed to the measurement system itself. For this study, one one ”operator” was used. Therefore, this study only measures Gauge R&R Repeatability - Gauge R&R Reproducibility is not measured.

Results

Visual Assessment

Figure 4 shows the visual impact of the different image processing approaches applied. The Raw (Gb) image shows staircasing effects along the edge. This can be attributed to the fact that by using only the Gb pixels, the image is effectively subsampled, and the image resolution is therefore reduced. The nearest neighbor approach shows severe aliasing artifacts. Visually, Malvar and Gradient demosaic shows visibly sharper edge reproduction. The ISP processed image shows visible edge overshoots.

AIAG Gauge R&R recommendations

% of Gage R&R of total variations (PRR)	
<10%	It’s considered to be an acceptable measurement system
>10% & <30%	It may be considered acceptable depending on application and cost factor, but try to improve it
>30%	It’s considered unacceptable and should be improved
Number of Distinct Categories (NDC)	
>5	Adequate Measurement System
=2	Data can be divided into say Low, High
=3	Data can be divided into 3 say Low, Medium, High
<2	Measurement system of no value for controlling system

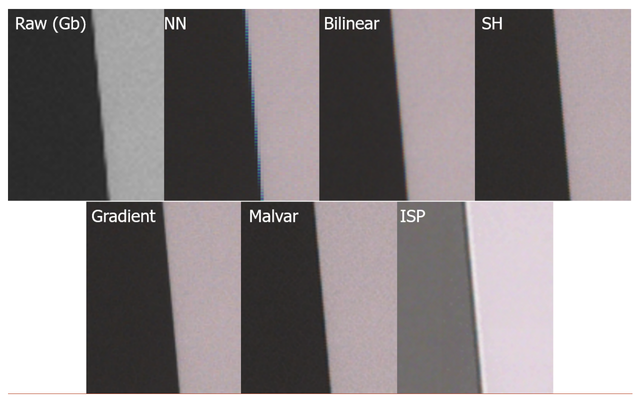

Figure 4. *Effect of image processing on edge characteristics*

MTF curves

Figure 5 shows the individual MTF curves at the point of peak focus for each image processing approach applied. The ISP processed curve shows characteristics overshoot due to edge enhancement. Additionally, the MTF at Nyquist is low, due to image denoising. The Raw (Gb) MTF curve has a higher amplitude than the other curves. This is due to the fact that the image is effectively subsampled. Nearest neighbor and bilinear both have low MTF values throughout the frequency range. This correlates with visual inspection results. Finally, Malvar has higher MTF at lower spatial frequencies, but lower MTF at higher spatial frequencies than the Gradient demosaic algorithm.

Through focus sweep

The average MTF50 from 30 images at each focus step for edge 1 (Figure 4) is shown in Figure 6. To identify the point of optimal focus, it is desirable for the curve to have a sharp peak. IF the peak is flat, the measurement system may not identify the point of optimum focus. From this through focus sweep, it is clear that the choice of image processing significantly affects the

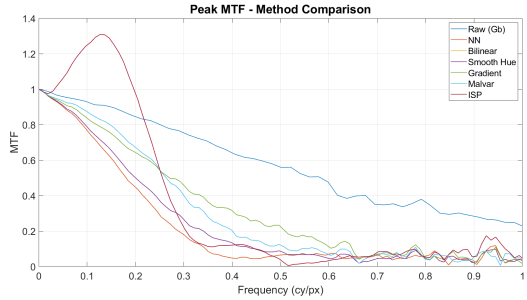

Figure 5. *MTF curves at peak focus*

shape of the through focus sweep. Again, the Raw (Gb) curve shows higher MTF50 results (due to the impact of subsampling) and a sharp peak. The ISP processed images demonstrate a flatter curve and wider distribution. A key observation is the fact that the point of peak focus, as indicated by the dashed lines, is not at the same focus step for all curves. Specifically, images processed by Malvar demosaic algorithm have a peak at one focus step earlier than all other image processing methods used. This is a concerning finding - by changing only the image processing, the point of measured peak focus is affected.

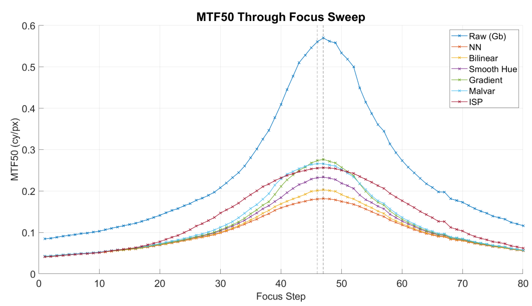

Figure 6. *MTF50 measurements during through focus sweep*

The coefficient of variation results are shown in Figure 7. The Raw (Gb) results show significantly higher variation than the demoisaiced or ISP processed image. Conversely, the ISP processed images show the lowest coefficient of variation. Also, the coefficient of variation tends to increase as mean MTF50 increases. This is especially clear in the case of Raw (Gb) and Gradient demosaic algorithms. In other words, as mean MTF50 increases, so too does measurement variability. From the point of view of camera manufacturing, this is clearly not a desirable result.

Gauge R&R results

Gauge R&R results are shown in Table 2. Raw (Gb) channel results show the highest levels of PRR and lowest NDCs. This indicates that this measurement configuration has the highest levels of measurement capability. Conversely, the ISP processed images have the highest NDCs and lowest PRR, indicating that this processing configuration has the best system measurement capability of the configurations tested in this study. Within the demosaic only configurations, Malvar shows the highest NDCs and lowest PRR.

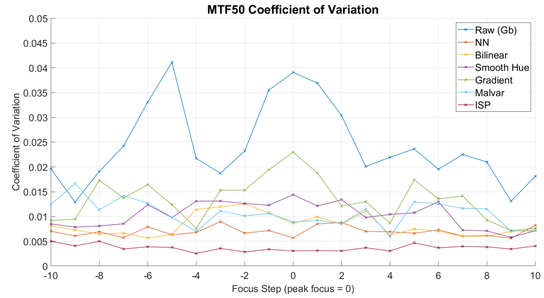

Figure 7. *Coefficient of variation*

Gauge R&R results

	Number of Distinct Categories (NDC)	% of Gage R&R of total variations (PRR)
Raw (Gb)	9	15.29
Nearest Neighbor	17	8.06
Bilinear	17	8.14
Smooth hue	17	8.23
Gradient	16	8.70
Malvar	19	7.58
ISP	26	5.33

Discussion

Manufacturing tolerances for modern automotive cameras are incredibly tight, due to the use case and functional safety requirements of the applications. As a result, manufacturers are required to carefully monitor, control and optimize all aspects of the camera production process, in order to ensure both product quality and profitability. Image processing and choice of demosaic algorithm has a very significant effect on MTF50. For the same through focus sweep, the peak MTF50 occurred at different focus steps, depending on image processing only. This clearly has significant implications for camera alignment. Furthermore, the high level of variance, and in particular, the correlation between variance and mean MTF50 score also present challenges for lens imager alignment. Based on the results of this study, Raw (Gb) MTF50 had the highest measurement variance. Conversely, ISP processed images demonstrated the lowest variance, and was the “best” configuration for camera manufacturing. However, this finding should be treated with an abundance of caution. As previously mentioned, edge enhancement can be used to artificially increase MTF scores even for poorly focused cameras. In the context of camera manufacturing, this is clearly not a good situation, as cameras not fit for purpose could end up in the field. It should also be noted that this is a pilot study only. In this work, the authors have examined results from one through focus sweep, primarily on a single slanted edge, for one camera. A more detailed study, involving multiple through focus sweeps, camera types, multiple measurement locations in the image and more image processing configurations is required before any definitive statements could be made. The results of this study do highlight that image processing has a significant effect on MTF measurements, and highlight the implications for automotive camera manufacture. Future work will examine MTF measurements from both centre and corners of the camera field of view, and the interaction between demosaic algorithms and edge distortion (particularly in the case of wide field of view cameras). This study focused on MTF50, due to its correlation with perceived image sharpness. There are multiple other MTF measurements which are also relevant for the automotive use case, including MTF at Ny/2 and Ny/4 (mid to low frequency performance), as well as MTF10 and MTF at Nyquist (limiting resolution). The impact of demosaic algorithms on these MTF measurements also warrants investigation. Also, only a small sample of demosaic algorithms was considered. Future work will also explore a wider range of demosaic algorithms described in the literature. This study has also only considered Bayer demosaic algorithms. Other sensor mosaic configurations such as RCCB, RCCG, RYYCy etc. also require investigation.

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Enda Ward *received his B.E. in Electronic Engineering in 1999 from the University of Galway and his MEng.SC master's degree in research in Electronic Engineering in 2002, with a focus on Biomedical Electronics. He is responsible for defining the camera product roadmap for surround and automated driving applications within Valeo. He holds several patents in the area of automotive vision.*

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