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Design of a Miniature Camera System for Interior Vision Automotive Application

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Abstract

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The purpose of this thesis is to describe the design process, goals, and analysis of the interior vision camera for a driver monitoring system. The design includes minimizing the overall footprint of the system by utilizing smaller more precise optics, as well as higher quantum efficiency (QE) image sensor technologies and packaging. As a result of this research, prototype cameras are constructed, and performance was analyzed. The analysis shows that Modulation Transfer Function (MTF) performance is stable at extreme hot and cold temperatures, while the cost is mitigated by using all plastic lens elements. New high QE image sensors are a potential improvement to this design. The mechanical part of the design has resulted in the filing of three different patents. The first patent was the athermalization spacer itself for automotive applications. The second patent was the way the lens barrel interacts with the athermalization piece. The third patent was the way the imager assembly accommodates the same Bill Of Material (BOM) components and different customer requirement angles.

Dedication

This thesis is dedicated to my parents Alena Fedarovich and Dzmitry Fedarovich. If it was not for their hard work and dedication, I would have never been able to have opportunities and success that I enjoy today. Thank you for my wonderful childhood, and I hope to keep making you proud!

Acknowledgment

Dr. Robert Bunch, thank you for serving on my advisory committee, for your corrections to my thesis, and for your advice during my time at Rose Hulman.

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Terms and Definitions

AA – Accelerated Aging

AFS – Automatic Focus Station

Aperture – an opening through which light travels

Astigmatism – error in an image that results in the Sagittal and Tangential SFR to be different within the same ROI

Blemish – a shadow of a physical object located in the way of OPD

BOM – Bill of Materials

Camera Space – 3D space of the camera assembly located in front of the object

Chief Ray - A chief ray is any ray from an off-axis object point which passes through the center of the aperture stop of an optical system

Chromatic Optical Aberration – error in image resulting in focus blurring when at least several wavelengths of light are introduced

Coma – error in image due to light rays off-axis that do not completely converge at the focal plane. Coma can be positive or negative.

Cpp – Cycles Per Pixel

CV – Concept Validation

Dead Pixel – Defective pixel that does not respond to light and is stuck in always OFF position

Distortion – error in image that does not affect focus quality but changes the shape of the object. Distortion is divided into positive (Pincushion) and negative (Barrell).

DMS – Driver Monitoring System

DOF – Depth of Focus at specific SFR

DR – Dynamic Range

DV – Design Validation

EFL – Effective Focal Length

EOL – End of Line

Extrinsic Calibration – Calibration of camera parameters from 3D physical Object location to 3D physical camera location

F-Number (F#) -Ratio of the system's focal length to the diameter of the entrance pupil. This number defines how much light information is available to the system

Fast Lens – Lens with a low F-number that allows for faster shutter speed to achieve the same amount of light exposure as a slower lens

FFT – Fast Fourier Transform

FFT – Final Functional Test

Field Curvature – error in image due to spherical nature of the lens

Field Testing – Vehicle testing performed with the product installed as expected in the customer's car.

Focus – optical point where light rays of a certain wavelength converge

FOV – Field of View

Gimbal – XYZ point of rotation located in the center of the Principal Optical Point of the lens.

Hot Pixel – Defective pixel that does not respond to light and is stuck in always ON position

ICT – In-Circuit Test

Image Space – 2D space of the image produced by the camera

Intrinsic Calibration – Calibration of camera parameters from 3D physical camera space to 2D projected image space

Lp/mm – Line Pairs Per millimeter, a special frequency unit

MTF – Modulation Transfer Function, a measure of focus quality

NIR – Near-Infrared spectral wavelength

OATTS – Optical Automotive Temperature Test

Object Space – 3D space of the Object located in physical space and observed by the camera

OEM – Original Equipment Manufacturer such as a big car making company

OPD – Optical Path Distance

Optical Axis – Central Axis of the Optical Path (Z-Axis)

Particle – a foreign object on the optical surface, such as dust.

Pixel Pitch – diagonal dimension of a single sensor pixel in SI units

Principal Plane – a plane in space near a lens where light ray appears to have crossed an inflection point

Principal Point – a point in space on a principal plane that intersects center axis of the Optical Path

PV – Production Validation

QE – Quantum Efficiency

ROI – Region of interest

SFR – Spatial Frequency Response, a measure of focus quality

SNR – Signal to Noise Ratio

Spatial Frequency – a measure of how often sinusoidal components of an optical structure repeat per unit of distance

Spherical Aberration – error in image that occurs when paraxial rays are focused further away from the lens then the peripheral rays

Stuck Bit – Data signal loss on one of the sensor data channels, resulting in a corrupt image

Vignetting - A fall-off in the illumination of the image. This can occur when the sensor is larger than the specified maximum sensor size of the lens is used or can naturally occur due to limitations of the geometry of the system.

1 Chapter 1 – Introduction

Motivation for this design is primarily drawn from the need to continuously improve the performance, cost, and efficiency of automotive consumer products. As newer technology comes available on the market, electronic camera devices become more robust, smaller, and cheaper. The result of this phenomena is that technology entrance into the market becomes a commodity and is implemented by all OEM car maker into the majority of vehicles and trim levels.

1.1 Thesis Organization

In this thesis, a design process of an automotive interior vision camera is derived from implementations that have been done previously, to design goals and improvements, leading to the new design. In Chapter 2, different solutions for interior vision are outlined. Previous designs and functions are reviewed and analyzed in order to understand future design goals should be. Design goals and considerations are thoroughly reviewed in detail in Chapter 3. In Chapter 4, measurement methods required to verify achievement of these goals are outlined and described. Chapter 5 contains the results of the design. End design patent features, metrics, and functions are described in this chapter. This chapter also gives a detailed description of equipment that was designed and developed in order to perform system evaluation. Designs of experiments that were performed using the equipment are also described in this chapter. Chapter 6 presents a summary of the results obtained by methods that are outlined in Chapter 4. Further design development for future plans are also outlined, and methods and technology not currently available to accomplish this design are also described.

2 Chapter 2 – Applications and Design of Automotive Cameras

2.1 Introduction

In this chapter, different types of automotive cameras are described along with components and design. The traffic environment of today consists of different vehicles, traffic, and information signs, and road markings, all designed for the human's visual system. Camera systems are very similar to the human visual system for machine perception of the surroundings, therefore they are great systems that offer similar spectral, spatial and temporal resolutions to the human eye. In addition, cameras can perform other helpful functions such as night vision (imaging in infrared region of the spectrum) and accurate distance measurements [1].

The first camera system to assist drivers was the rear-view camera, which gives the driver a live view of behind the car on a monitor system. This type of camera which monitors the car's surroundings is called exterior cameras. Cameras can also be used to monitor the driver, for example by monitoring the driver's gaze or gesture, this type of camera is called the interior cameras. The design for each of these camera types is different from each other [1].

2.1.1 Driver and Interior Detection

For monitoring the driver and inside the car, since the distance between the object and the camera is smaller, the optical parameters such as the depth of focus (DOF) will be significantly different from the exterior cameras. Also, for the camera to be able to ensure a high-quality image when there is poor lighting and when the lighting conditions change quickly, an artificial light source in the near-infrared (NIR) spectral region is selected. The NIR light source has another advantage that it is invisible to the human eye [1].

2.1.2 Environmental Detection

The environmental detection gives full identification of all related road users, road scenery and road signs in order to be able to react appropriately. For this to happen, a variety of different sensors is required. In Figure 1, an example of this situation is shown.

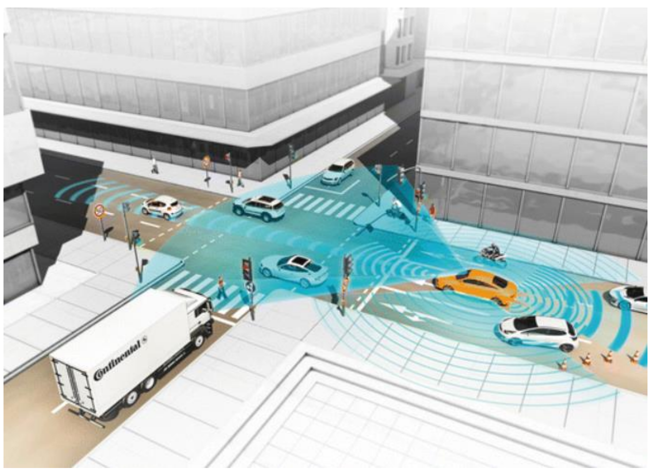

Figure 1 - Environmental detection by different sensor systems [1]

Figure 1 shows the field of view (FOV)s are overlapping, which guarantees different detection ranges. In this picture the sensors are various range RADAR sensors [1].

2.2 Design of Driver Assistant Cameras

This section describes some basic design aspects of the automotive cameras discussed in the previous section. The basic architecture of the driver assistant camera is shown in Figure 2, an image of the object is projected through an imaging lens onto the image sensor. At this point, the image sensor's pixels convert the optical input to an electronic output signal, which is then processed by a computing unit and showed to the user on a screen [1].

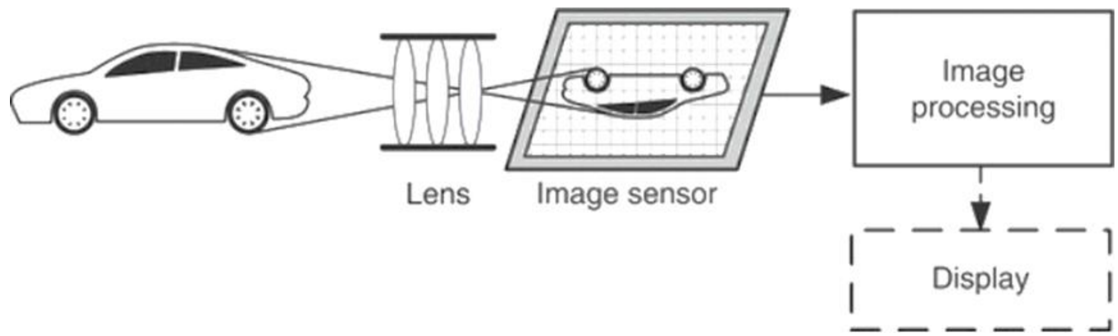

Figure 2 - Schematic of how a basic driver assistant camera works [1].

2.2.1 Criteria of the design

To design a camera system there are a lot of parameters and components that play important roles to provide optimal performance. The first crucial component is the lens as shown in Figure 2. The properties of the lens such as the FOV, depth of field, resolution, and sensitivity is important in the overall performance of the lens. Since an optical system can never create a perfect image, potential errors such as distortion must be corrected [2]. In the next step, the image created by the lens is converted into digital values by the image sensor. This means the design of the sensor is very important. The optical system is typically adapted to the sensor, which is an essential step to the image performance at the end. The sensor mostly effects the FOV, resolution (number of pixels), dynamic range, color reproduction and notably the sensitivity [1]. Finally, as shown in Fig.2, the image processing procedure influences the image quality.

2.2.2.1 Field of View (FOV)

The FOV of the camera plays an essential role in the overall performance of the system, which is defined by the image sensor and the lens. The FOV can be defined in vertical and horizontal directions (VFOV, HFOV) as shown in Fig.3. To calculate the field of view Eq. 1 is used. "h" being the mounting height and "d" minimum detection distance. The datum point of mounting reference is defined by every OEM differently.

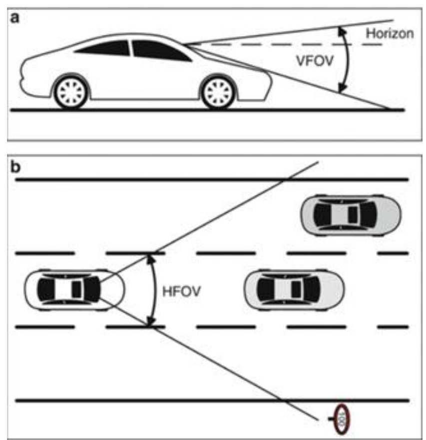

Figure 3 - HFOV and VFOV.

$$\alpha = tan^{-1}(\frac{h}{d}) \qquad (1)$$

Large HFOVs are required for exterior cameras (more than 40°), for lane detection (tight curve situations) and object detection (pedestrians and crossing vehicles). In exterior cameras, the HFOV is usually more than 100° [1]. For cameras, the head of the driver should be imaged, which requires 40° to 50° HFOV. In order to be able to monitor the driver's gesture, usually, a camera module is in the functional unit in the dashboard, with HFOV >50° [1].

2.2.1.2 <u>Camera Resolution</u>

The resolution of the camera is a combination of the lens resolution, the resolution of the image sensor and the image processing. The first step in designing a camera is to theoretically analyze the system. The object needed to be imaged is analyzed which gives the resolution required for image processing. The next step is to find the necessary resolution in terms of pixels per degree based on geometrical relations. Values are usually >15 pixels per degree for driver assistance systems [1]. In the case of exterior cameras, the camera resolution is important, especially in recognizing road signs. Fig.4. shows the results of using cameras with different resolutions. For the case of interior cameras, the resolution is very important for detecting the eye movement of the driver [1].

Figure 4 - Effect of decreasing resolution using the example of a traffic sign.

2.2.1.3 <u>Color Reproduction</u>

Color reproduction and being able to display a realistic representation of the camera image on the monitor is crucial so is the ability to distinguish between different objects. In Fig.5, the importance of distinguishing color is shown. In the case of a monochromatic camera, both yellow and white solid lines appear as the same color. While in the case of the camera with color separation abilities, this issue is not observed. [3]

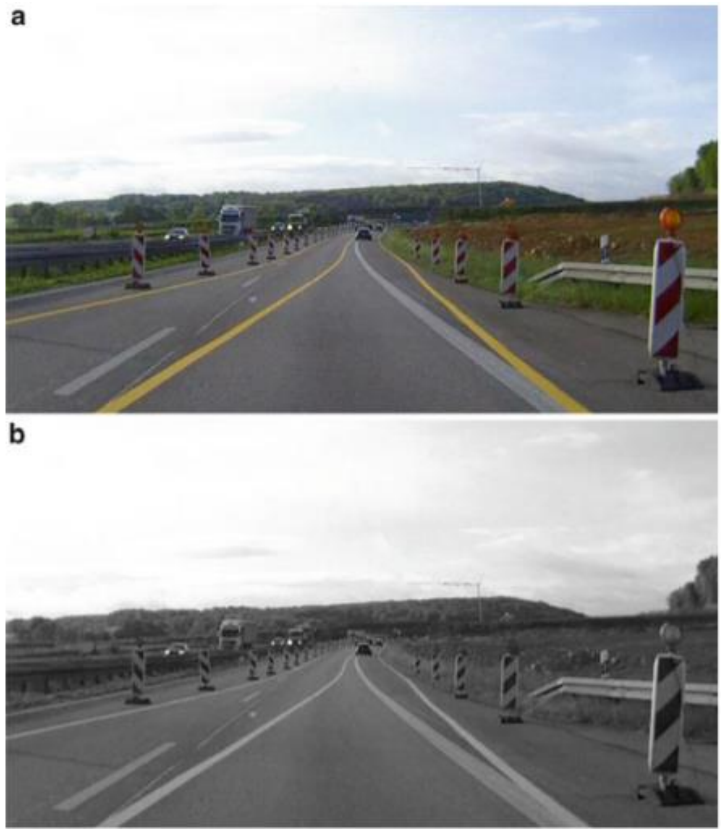

Figure 5 - (a) color image showing lines to be detected, and (b) a monochrome image where the lines cannot be distinguished [1].

2.2.1.4 Dynamic Range

The dynamic range of a camera system is the system's ability to image dark and bright areas. The noise limit of the image sensor limits the dynamic range in the dark areas and the saturation limit of the image sensor limits the bright areas. The dynamic range of the camera and the optical path length also play a significant role in the overall dynamic range [4]. The dynamic range is also affected by stray light, causing ghosting and flare which decrease the quality of the image. In the case of low-standing sun, entrances/exits of tunnels, parking garages, and cars in the reverse lane during night time, there is a challenge with image performance. A pavement marking displays luminance of 10 cd/m^2 while headlights of a car in the can have a luminance up to 100000 cd/m^2. These issues can be lowered by designing a system with a high dynamic range, as shown in Fig.6 [4].

Figure 6 - Traffic scene with high dynamic range.

2.3 Camera Module

Camera modules are defined as a combination of lens, image sensor, electronics and packaging. They have different designs. As an example, a camera module, as shown in Fig.7, is described in this section, with all the important parts explained.

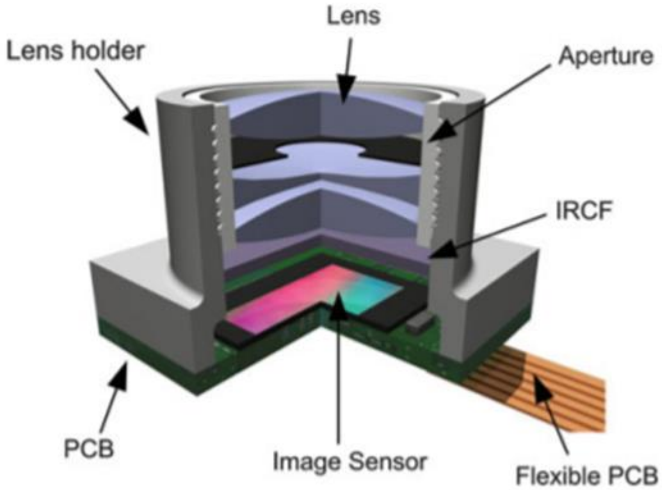

Figure 7 - Schematic structure of a camera module [1].

2.3.1 Optics

The camera lens usually consists of several single lenses, optical filter components and the overall lens housing. The design of the optical parts of an automotive company is a trade-off between the optical operation, costs and durability. This trade-off affects the material used for the single lenses, numbers and the choice of material for the housing.

2.3.1.1 Lens Design

Since standard crown or flint glasses are moderately priced, they are the materials usually used for the lens elements. Sometimes lenses made from plastic might be used but since they might not tolerate high temperatures there is a limit to a number of plastic lenses used in the design of the camera. Plastic lenses are manufactured by injection molding. They are available in spherical and aspherical shapes [1]. For driver assistance purposes the camera is usually delivered in a water and humidity proof housing. The cover of the housing is normally black or covered by a black coating to minimize the stray light. For cameras with driving assistance purposes a bandpass filter is used to suppress all light except for the required NIR light. An extra UV filter is used to filter out the UV radiation. It is important that all optical elements are coated with anti-reflection coatings [1].

2.3.1.2 Optical requirements based on the application

The lens design is based on the purpose of the system. The most important parameters affecting the lens design procedure is the FOV, image distortion, light sensitivity, and image sharpness [5].

2.3.1.2.1 Image Sharpness

A camera's ability to produce a sharp image is described by the Modulation Transfer Function (MTF). The MTF defines how close the image is to the object being imaged. The image sharpness changes along the optical axis [2].

2.3.1.2.2 Aberrations

The aberrations which affect the automotive camera lens design are spherical, coma, chromatic, astigmatism, and field curvature. Usually using more lenses or more expensive lenses helps reduce the aberrations [1].

2.3.1.2.3 Image Distortion

Image distortion up to a few percent can be fixed by software algorithms. This means that designing a very costly camera with 0% distortion is not necessary [1].

2.3.1.2.4 Image Sensitivity

Low sensitivity is usually achieved by a low F-number system design, which compensates for low light conditions. This can be done by using a large aperture and/or a small focal length. On the other hand, large apertures import more aberrations into the system, which can be reduced by adding more single element lenses [2]. The lenses for interior cameras monitor the driver within the range of 40 to 100 cm. For this range, the F-numbers have to be at least 2 since the system has to have a large depth of focus [1].

2.3.2 Image Sensor

There are two types of digital image sensors based on architecture; *Active Pixel sensors* and *Passive Pixel sensors*. Active Pixel sensors are manufactured using CMOS technology. In this case each pixel is actively and individually converting charge to voltage, then converts that to a digital signal using an integrated analog-to-digital converter [6]. For Passive Pixel sensors as in CCD sensors, the charges created in each pixel and converted to an output voltage of that pixel by being transferred to a common conversion node [7]. There are different factors which effect the performance of image sensors, including sensitivity and noise, resolution, dynamic range and color reproduction [8]

2.3.2.1 Sensitivity and Noise

The overall noise performance of a sensor affects the sensitivity of the sensor. The noise performance of the sensor is very important over the required temperature and other conditions. The image sensor noise includes temporal noise, photon shot, spatial noise [7]. At very low signal levels, the temporal noise plays a crucial role in the overall noise. Whereas photon shot noise is more important in medium to high signal levels [1]. Spatial noise appears if there are any differences in the gain and offset for each pixel, which is usually a result of changes in the current to voltage conversion rate in active pixels. There is a nonlinear dependence between spatial noise and the temperature of the sensor [1].

2.3.2.2 Resolution

The only parameter that impacts the quality of a digital video is not just spatial resolution (number of pixels on which an object is imaged) but also contrast resolution (number of gray levels in a scene which can be resolved) and temporal resolution (time interval between two images).

2.3.2.3 Dynamic Range

The dynamic range for an image sensor is the range of intensities that can be resolved. The saturation level of pixels and the signal to noise ratio limit the dynamic range. Linear sensors have a dynamic range of 60-70 dB which is not enough for representing the entire dynamic range of the scene. HDR sensors have a dynamic range of around 120 dB, which translates to an expected contrast ratio of 1:1000000 [9], [1].

2.4 System Architecture

In order to be able to meet all the system requirements, the system's hardware and software elements and image processing algorithms have to be designed and programmed correctly. Also, the mechanical design and the connection of the mechanical and electrical components with the vehicle is very important. Drivers assistance cameras are vehicle components related to safety, and the system has to abide by the (road vehicles- functional safety) [10].

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2.4.1 A Glimpse of the system

An overview of a driver assistance camera system in Fig.8, shows different components of the camera system including image acquisition, control, processing, and communication with the vehicle. The camera system can be designed as a single unit or as a system with separate components (like the camera module separate from the image processing unit) [1].

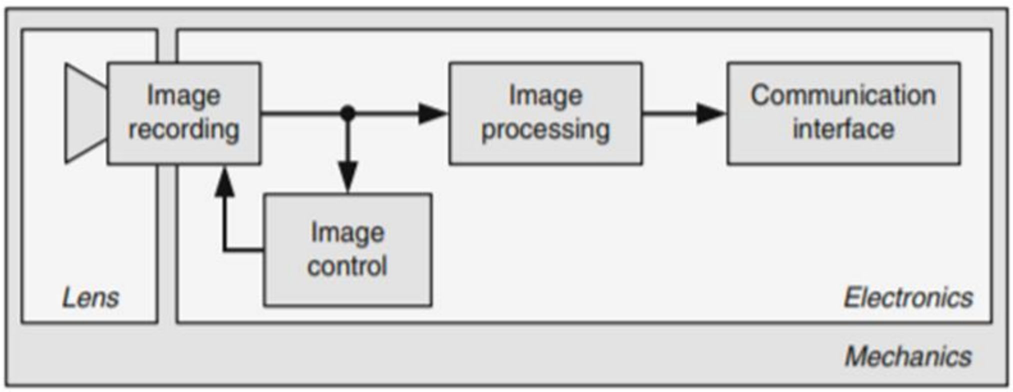


Figure 8 - Overview of a driver assistance camera system [1].

2.4.1.1 Image Acquisition

The image is recorded by using one or more camera modules in the vehicle, for both exterior or interior cameras. The Image Acquisition Control then impacts the image which is then sent for image processing.

2.4.1.2 Image Acquisition Control

Before the image is captured, the system is set to optimal image parameters. In order to be able to adjust to different lighting situations the *Exposure control* makes sure that the image is not either oversaturated or undersaturated. *White balance* ensures that images have consistent colors, even if the light source has a different color temperature [11].

2.4.1.3 Image Processing

After an optimal image is captured, input values from the image are transferred to output values going through a transformation step. If the image is displayed on a screen, it has to go through noise reduction, edge enhancement and color correction before being displayed [11].

2.4.1.4 Communication

The communication interface of the camera system is responsible for data exchange between other controllers in the vehicle [1].

2.4.1.5 Electronics

The design of the electronic parts must follow high standards in the automotive industry, including durability and electromagnetic immunity and compatibility. A large amount of data must be processed in real time, which causes the system temperature to rise, which is always a challenge.

2.4.1.6 Mechanics

The housing of the camera is the boundary between the electronics and the camera module. It is required that it is thermally stable and is sealed against humidity.

2.5 Calibration

In order to ensure that the functions serve their purpose, it is crucial that the images captured by the camera are interpreted correctly. There is certain necessary information which can be subtracted from the image using calibration algorithms. This information is used to compensate for deviations from the defined norm. An example is the linearization of the response curve of the image sensor [12]. Depending on the characterization to be studied, calibration parameters are categorized in two different classes of parameters to be mentioned below (intrinsic and extrinsic calibration).

2.5.1 <u>Depiction of the camera module</u>

Opto-electronic conversion function is an Image Sensor's response curve. In order to find the OECF, with defined illumination intensities and constant exposure times, a few images are captured. This helps to find the response curve of the sensor. This curve predicts the behavior of the sensor, and if there are any deviations from the desired manner, it can be compensated [1]. Noise created by dark current (defective pixels) [1]

2.5.2 <u>Geometrical camera calibration [1]</u>

There are two types of geometrical camera calibration parameters – intrinsic and extrinsic. Intrinsic are the parameters associated with location from the point of view of the camera system, while extrinsic are parameters associated with camera location regarding external space. Intrinsic parameters include camera principal point, focal length, distortion, and pixel scale factors. Extrinsic parameters include camera position and camera orientation in space.

2.5.3 <u>Calibration procedures [1]</u>

Intrinsic camera calibration is performed on the camera production line. It usually consists of a checker board target is used with a 3D setup. By knowing the geometry and the corners of the target and their positions in the captured image, the intrinsic calibration parameters of the camera can be found. Extrinsic camera calibration is performed on a vehicle production line. Cameras can’t be completely calibrated during the camera production line since the camera is not located at its final position and depending on the load of the car. Extrinsic camera calibration is also performed while the vehicle is functioning. Even though calibration is prior to the final step, the system still needs to be re-calibrated while the system is in use. Changes in temperature and mechanical conditions can affect the system’s performance.

3 Chapter 3 – Design Goals and Considerations

Introduction

DMS3 Imager product is intended to be compatible with DMS2 data analysis platform software (vehicle algorithm), as well as compatible with current manufacturing equipment, as well as manufacturing outsourcing partner equipment. Design features shall accommodate the following design goals: automotive application compatibility and performance; 6-axis alignment, regardless of whether it is lens to imager or imager to lens type of alignment; minimal electrical components; minimal BOM costs; athermalization performance that achieves less than 2% MTF shift at temperature (-40C and +85C); maximum efficiency image sensor at 940nm wavelength that is cost-effective regarding BOM cost; Vehicle Platform angle control via front locking ring variants.

Camera Design

This section outlines PCB requirements and Image Sensor requirements that are considered in the design. PCB is tailored to the application, while the sensor is selected from off-the-shelf models available on the market.

3.1 PCB

Image Sensor PCB, as shown in Fig.9, shall consist of two separate rigid substrates connected via rigid flex connector. The first rigid substrate shall be a 4-layer standard 1.4mm FR4 printed circuit board. The up-side shall contain an image sensor only, and the keep-out surface area for the lens housing bond line. The other side of the first substrate shall contain components required to provide power and signal output via parallel interface to the main board through the second substrate containing a board-to-board connector. On the back of the connecting rigid-flex PCB there shall be 15 1mm diameter electronic circuit test points, required for active alignment and in-circuit test analysis. This is also required for any manufacturing testing of the imager board and must obey the manufacturing standards and practices specific to the manufacturing plant [13].

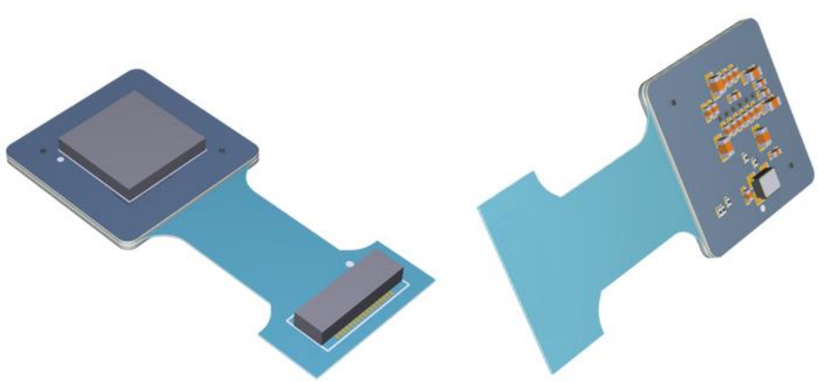


Figure 9 - Schematic of the PCB used in this thesis.

3.2 **Image Sensor**

Image sensor variants that are listed in Table.1 are the closest match appropriate for interior vision automotive application. Specification parameters listed are also described in more detail below.

Table 1 - Image sensor variants.

Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8
OV2311	X2C	X1H	OV2310	OV9284 - No Functional Safety, cheaper option	AR0135AT	AR0234AT	AR0232AT
1600x1300	1600x1300	1300x1000	1300x1000	1280x800	1280x960	1920x1200	1920x1200
2MP	2MP	1.3MP	1.3MP	1MP	1MP	2MP	2MP
3	2.2	2.2	3	3	3.75um	3um	3um
OmniVision	OmniVision	OmniVision	OmniVision	OmniVision	OnSemi	OnSemi	OnSemi
13%	40%	40%	13%	13%	8%	8%	35%
Global	Global	Global	Global	Global	Global	Global	Global
No Underfill	No Underfill	No Underfill	No Underfill	No Underfill	No Underfill	No Underfill	No Underfill
Venus Board	Venus Board	Venus Board	Venus Board	Venus Board	Aptina Demo3	Aptina Demo3	Aptina Demo3
7219um x 6157um	Not available	Not available	7219um x 6157um	5237um x 4463um	9x9	11.5x7	11.5x7
MIPI	MIPI	MIPI	MIPI	MIPI	HiSPi	MIPI	MIPI
10bit	Yes	Yes	10bit	10bit & 8bit	12-bit	10-bit	10-bit
37.4dB	Not available	Not available	37.4dB	38dB	40.7 dB	38 dB	Not available
68dB	Not available	Not available	68dB	68dB	71.1 dB	71.4 dB	Not available
190mW	<200mW	<200mW	155mW	156mW	<292 mW	Not available	Not available
a-CSP	a-CSP and a-BGA	a-CSP and a-BGA	a-CSP	a-CSP	iBGA, Bare Die	iBGA	Not available
Mono	Mono	Mono	Mono	Mono	12bit Monochrome	12bit Monochrome	Not available
60	60	60	60	120	54 FPS	30 FPS	Not available
-40/105C	-40/105C	-40/105C	-40/105C	-40/105C	-40/105C	-40/105C	Not available
-40/120C	-40/120C	-40/120C	-40/120C	-40/120C	-40/120C	-40/120C	Not available
15deg linear	Not available	Not available	11.9deg linear	26.78deg non-linear	0,25Deg	15,28Deg	Not available

3.2.1 Active Pixels, Resolution, and Pixel Size

The number of active pixels, resolution, and pixel size are primarily related to the performance requirements of the Vehicle Platform Algorithm. The object which needs to be detected is the pupil of the eye. The two primary current techniques for detecting the gaze vector are the dark pupil and bright pupil detection. Since the pupil detection is heavily dependent on the application, the following explanation of the concepts in section 3.2.2. and 3.2.3. is important to understand [14].

3.2.2 Bright Pupil Detection

For bright pupil eye tracking as shown in Fig.10, an illuminator is placed close to the optical axis of the imaging device, which causes the pupil to appear lit up (this phenomenon is responsible for the red-eye effect in photos) [15].

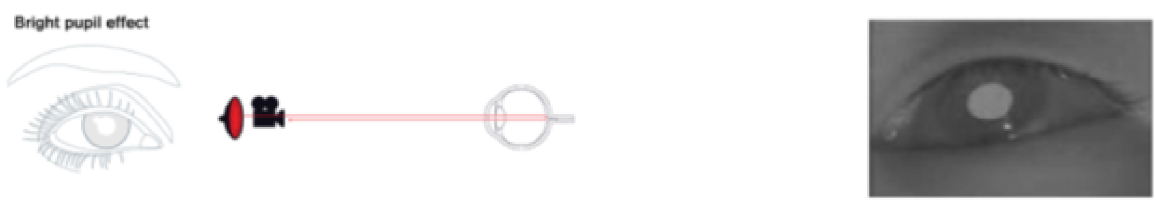


Figure 10 - Bright pupil detection system [16].

3.2.3 Dark Pupil Detection

For dark pupil eye tracking, an illuminator is placed away from the optical axis, which causes the pupil to appear darker than the iris [15]. The schematic is shown in Fig.11.

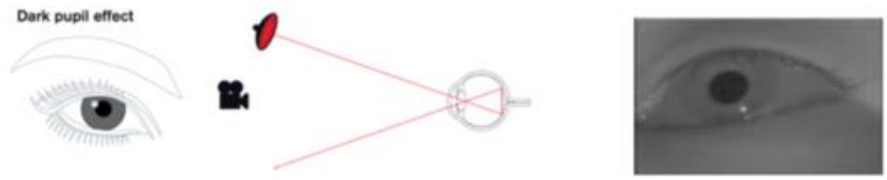


Figure 11 - Dark pupil detection system [15], [16].

3.2.4 Minimum Resolution Required from camera

Rs is the spatial resolution (can be either X or Y). FOV is the field of view dimensions (mm) in either X or Y directions. R_i is the image sensor resolution; number of pixels in a row (X dimension) or column (Y dimension). R_f is the feature resolution (smallest feature that must be reliably resolved) in physical units (mm). F_p is the number of desired pixels that will span a feature of minimum size. For example: FOV(x) = 40mm, R_f = 0.25mm, F_p = 4 pixels. Calculating the spatial resolution (Rs) needed, therefore $R_s = R_f / F_p$ = 0.25mm / 4 pixels = 0.0625mm pixel. From the spatial resolution (R_s) and the field of view (FOV), we can determine the image resolution (R_i) required (we have only calculated for the x-axis) using $R_i = FOV / R_s$ = 40mm / 0.0625 mm/pixel = 640 pixels equation. We have now determined that we need a minimum resolution of 640 pixels in the x-axis to provide 4 pixels across our feature that is 0.25mm in diameter. The camera resolution can now be selected [17].

3.2.4.1 Minimum object detection principle

There are several functions that Interior Vision Camera System must support. Included but not limited to Face ID, Cellphone recognition, seatbelts, driver fatigue, distraction, and drowsiness.

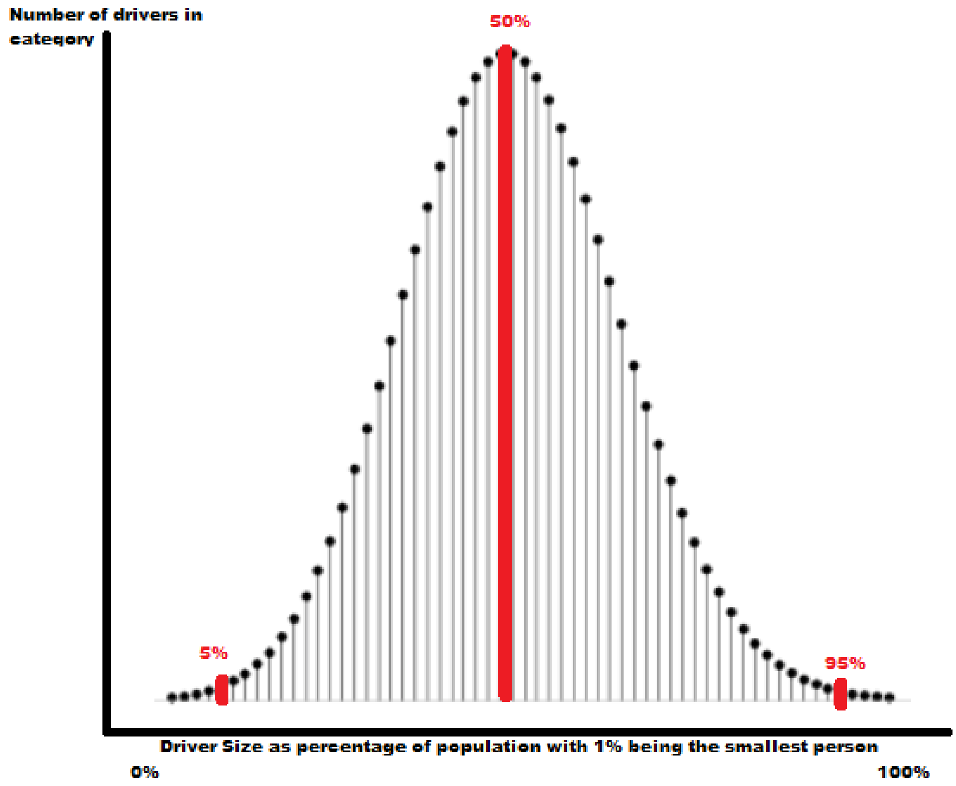
The smallest detectable object in the scene is the human eyeball, and the glint from the reference illumination system.

3.2.4.2 Minimum pupil size

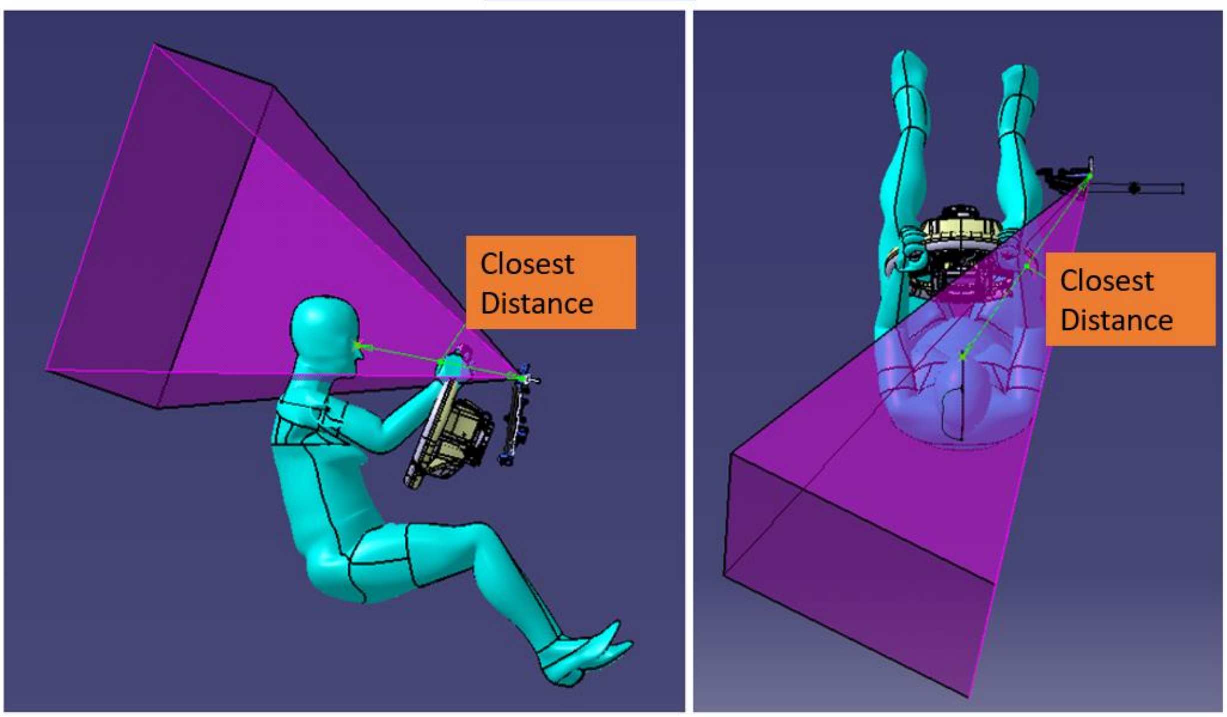
The normal pupil size in adults varies from 2 to 4 mm in diameter in bright light to 4 to 8 mm in the dark. The pupils are generally equal in size and this pattern is used in the detection algorithm [18]. Depending on the background light intensity, the minimum pupil size is given to the system and information is used in calculations.

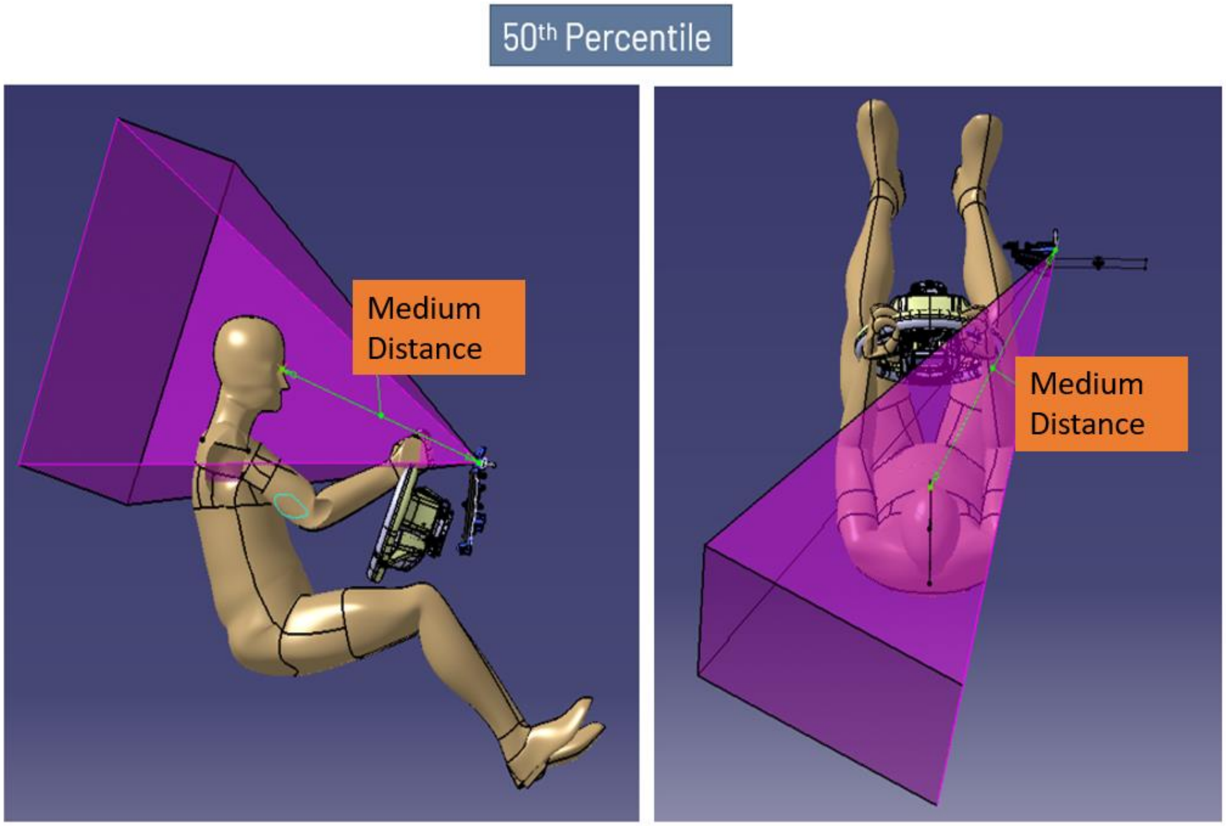
3.2.4.3 Minimum driver head distance

According to Fig.12, the minimum distance between the driver's head and the camera depends on the height of the driver. Below different driver sizes illustrate different adjusted camera positions. Driver sizes are typically analyzed by statistical population distribution generated in the form of a Poisson bell curve. The fifth percentile would mean smallest size drivers on the left side of a bell curve, fiftieth – the middle and most probable driver size, and ninety-fifth would be the largest size drivers.

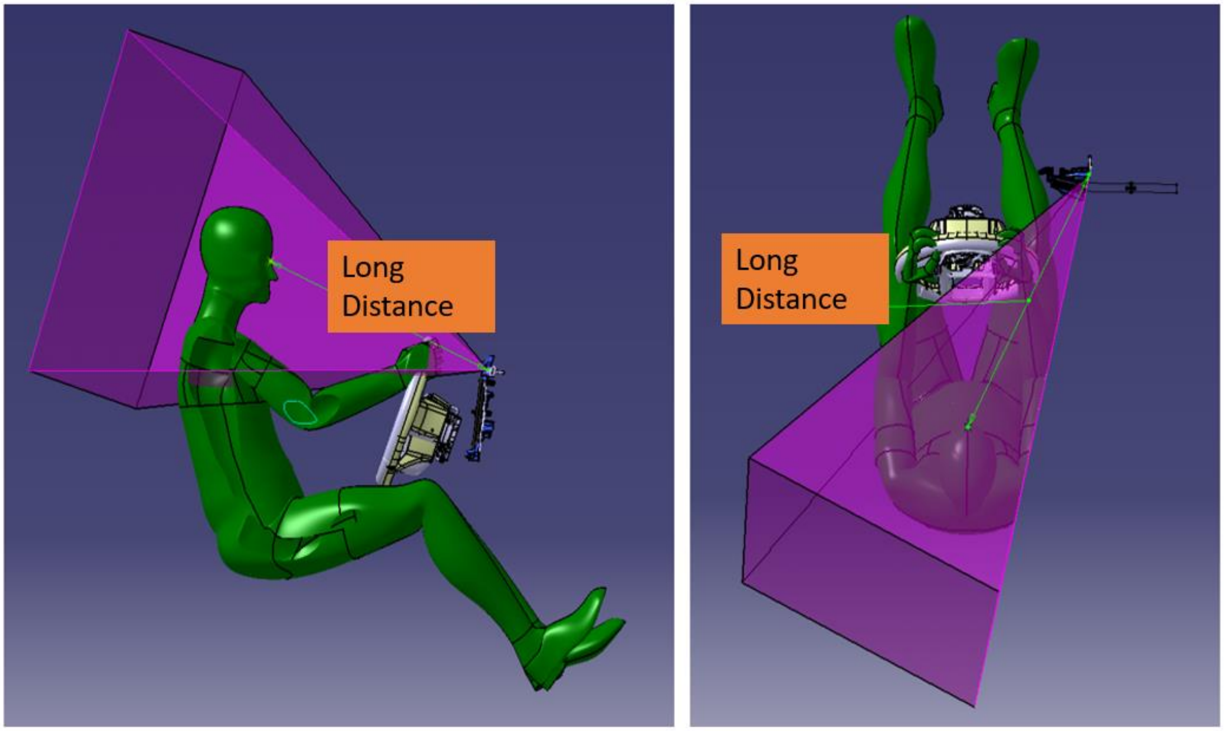


5th Percentile




50th Percentile
Medium Distance
Medium Distance

95th Percentile



99th Percentile

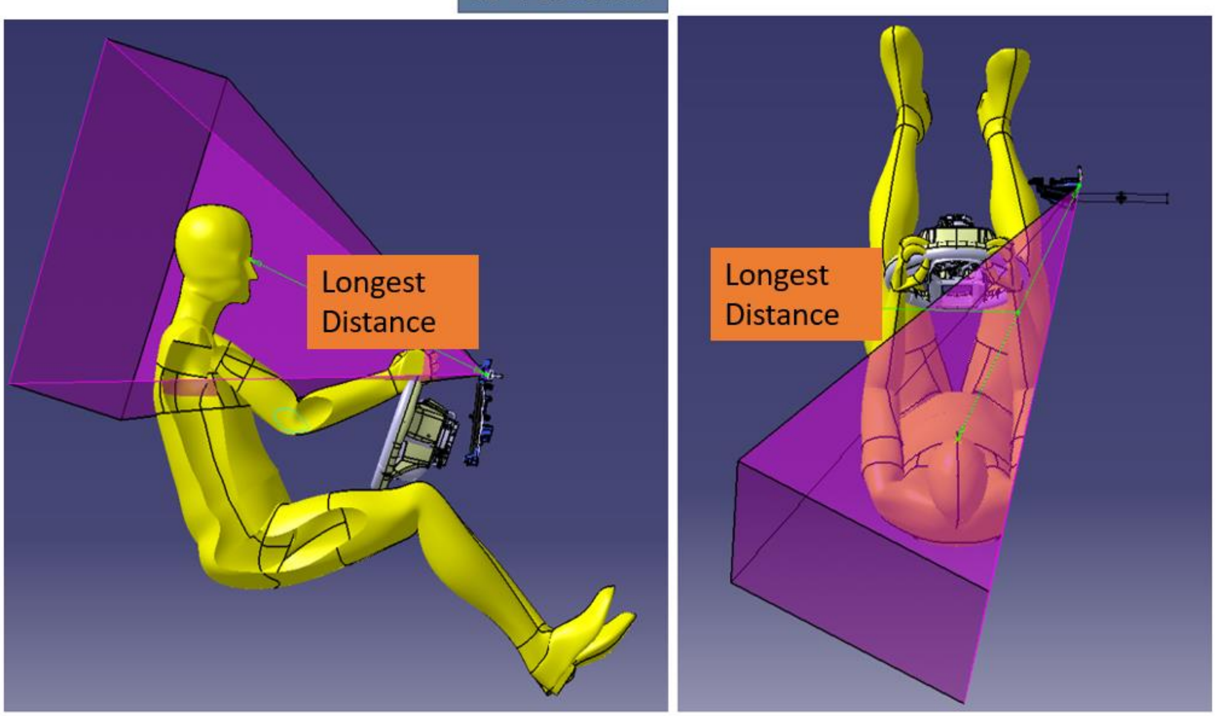


Figure 12 - Minimum driver head distance for different heights.

3.2.4.4 Camera Field of View

For Interior cameras, the head of the driver is required to be imaged, which requires 40^o to 50^o FOV. In order to be able to monitor the driver's gesture, usually, a camera module is located in the functional unit in the roof, with FOV >50^o [1].

3.2.4.5 Manufacturer, Pricing, and Development

A comparison between three different Image sensors is shown in Table.2.

Table 2 - Comparison of the performance for different Image sensors.

		Score		
Parameter	**Weight**	**OnSemi**	**Sony**	**OVT**
Performance	3	2	3	1
DevKit	3	3	1	2
Cost	3	2	1	3
Software	3	3	1	2
QE Technology	3	2	3	3
Packaging	3	3	3	2
Total Score		15	12	13

Sony Image Sensors have excellent performance but higher cost. Imager development kits tend to be a larger size and cumbersome to work with. Software is more difficult to use, and customer support needs improvement. ON Semiconductor Image Sensors have a good performance, the software is good and easy to use, many packaging options are available, and customer support is excellent. Image Sensors are expensive, QE at low light is low. Omni Vision Technology (OVT) Image Sensors have a good performance, lowest price on the market, superior low light performance, customer support is excellent, smallest package size, backlit pixel technology is SOP earlier than others. Development software is hard to use, underfill might be required due to joint cracking issues, and development kits are cumbersome. Any of the above evaluation statements are only true to a specific point in time when the evaluation was performed. These statements are highly subjective, not absolute, and should not be used by anyone as absolute facts, and do not represent anything other than an opinion of the author.

3.2.4.6 Quantum Efficiency

Quantum efficiency (QE), as shown as a function of wavelength in Fig.13, is the percentage of electrons produced from the number of incident photons. Increasing QE improves sensor signal to noise ratio and dynamic range. Because QE is a complex function of the photodetector type, the processing technology, and the physical layout, in general it cannot be determined analytically or using simulation. Instead, it must be measured [19]. As the quantum efficiency of an image sensor increases, the price increases too because it means a higher conversion rate of photons to electronic signal [20].

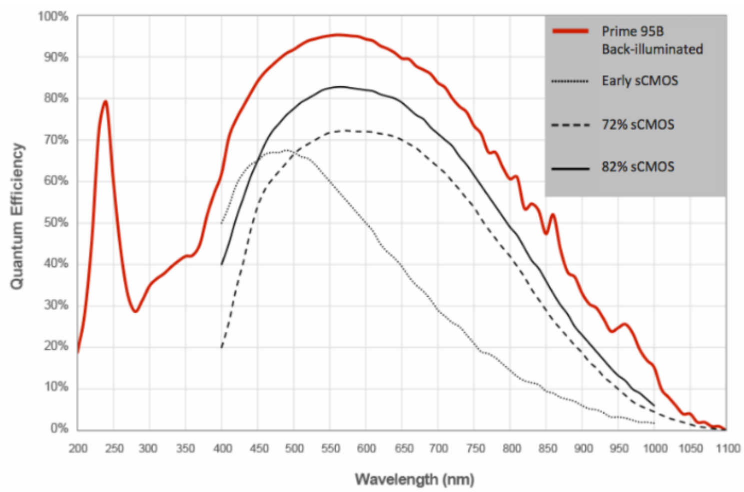


Figure 13 - Comparison of the QE with four different Image sensors [20].

3.2.4.7 <u>Shutter</u>

Rolling Shutter means that adjacent rows of pixels are exposed with a time offset as the readout sweeps through the image sensor. Generally, from a readout perspective the sensor is split in half, and each half runs offset row sweeps simultaneously. As the wave of the readout is sweeping through the rows, each row is drained of charge that collects inside the sensor. The charge that is drained is then transferred through a readout node of each pixel and converted into digital signal. Each row of each half of the sensor is subject to the same readout time. However, there is an offset of about 10 microseconds between the rows. Normally Rolling Shutter operates in continuous mode, so no photons are wasted. This ensures 100% duty cycle, meaning that no time and information is wasted in between. The biggest downside of the rolling shutter is spatial distortion and time lapse between the exposure cycles of the halves of the image sensor resulting in synchronization issues. The resulting effect is sometimes referred to as wobbling. The reason why rolling shutter is still used in cameras, is because it allows for less noise, wider dynamic range, and less heat generated [21]. Global Shutter means that all CCD array pixels are exposed and read out at the same time, freezing the frame at the time of readout. Before the exposure begins, all pixels are held in a clean state mode free of charge, which is drained into an anti-bloom structure of each pixel. At the start of the exposure each pixel begins to saturate with charge for the duration of the cycle. At the end of exposure, all pixels drain into respective readout nodes, that are then converted into a digital signal. One of the disadvantages of the global shutter, is that it requires a reference readout that continuously runs in the background. This phenomenon increases the noise and reduces the dynamic range of the camera [22]. Two different Shutters have been compared in Table.3 below.

Table 3 - Comparison of rolling shutter and global shutter. Most critical parameters are marked in red.

Function	**Rolling Shutter**	**Global Shutter**
Snapshot Exposure	No	Yes
Interline similarity	No	Yes
Temporal correlation between different regions of image area	No	Yes
Synchronization capability	**Requires Strobe Light**	Works with any light
Fast Double Exposure Capability	No	Yes
Maximum Frame Rate Read Noise	Max	1/2 Max
Spatial Distortion	**Yes**	No
Duty Cycle Efficiency	Low	High
Price	Low	**High**
Power Consumption	Low	High

3.2.4.8 Size

Package size of the imager is important because minimizing the footprint of the product will help attract more business and interest from customers, given that the performance is maintained. Nowadays, customers want smaller and smaller electronics. Also, minimizing the required Instrument Panel footprint gives OEM an ability to place the product in a lot more locations, making the appearance more attractive and lowering development costs [23].

3.2.4.9 Parallel and Serial Interfaces

Parallel interface is when data is transmitted simultaneously across multiple electrical conductors (channels) via a physical layer. Channels operate via the same clock speed making data transfer eight times faster than in Serial Interface. The speed of the data link is equal to the number of bits sent at any one instance. One of the drawbacks of the parallel interface is the footprint required to run multiple traces on a printed circuit board, as well as the interference between the lines, called “crosstalk.” Generally, this highly limits the length of the data link, making this method unsuitable for long-range data transfer. Alongside an advantage of being faster than serial communication, parallel communication is also simpler to implement in an integrated circuit system, as it does not require any translation/manipulation of digital data [24].

Serial interface is the opposite of parallel. Every piece of data is converted into a binary group and then sent via single channel to the receiving end, where it is converted back into original format. The device required for sending the data is called a “serializer” and device that is required for converting data into original format is called “de-serializer.” The biggest advantage of this system is scalability to a long-distance format, which is sometimes required for a specific camera application. Because there is less crosstalk due to only one data channel, data can be sent via coaxial cable over long distances. The biggest disadvantage of the serial communication is the fact that additional hardware is needed, such as serializer, de-serializer, and power supply infrastructure to allow for data signal amplification. In return, this also increases the costs, and footprint of the camera system [24]. Schematic for both parallel and serial interfaces is shown in Fig.14.

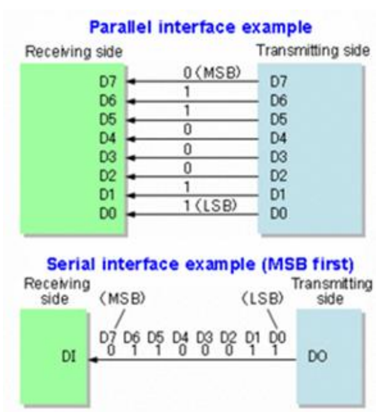


Figure 14 - Schematic of parallel and serial interface.

3.2.4.10 **SNR**

Signal to Noise Ratio is an important factor when selecting an image sensor. Higher Signal to Noise Ratio is a secondary priority factor. Normally it is a byproduct of design goals of the image sensor manufacturers. The byproduct of low Signal to Noise ratio is an inability to detect objects in the scene correctly or having to filter the noise [25].

3.2.4.11 **Dynamic Range**

Dynamic Range is an important factor when selecting an image sensor as well. Detailed measurement of Dynamic Range and description are outlined in section 3.5.16. Higher Dynamic Range is a secondary priority factor, because normally it is a byproduct of design goals of the image sensor manufacturers. However, having a higher dynamic range camera system results in better contrast between the objects, allowing for more precise object detection [26].

3.2.4.12 **Power Consumption**

Lower power consumption is desired and results in less heat produced by the assembly, reducing the need for heat sinking, as well as smaller power supply components, which in return reduces the footprint and cost of the entire system.

3.2.4.13 **Types of Packages**

IBGA Imager packaging, as shown in Fig.15, stands for Interstitial Ball Grid Array image sensor package. Ball Grid Array sensor must be first placed and tacked onto a printed circuit board via "Surface Mount Technology" SMT, and then heated with a Reflow Oven in order for the balls to melt and integrate with the PCB leads. There are many disadvantages to this technology such as solder joint cracking, placement accuracy, long term unreliability, and optical misalignment error in case of image sensors. Alternatively, the advantage of the technology is a reduction in the overall footprint of the image sensors and this technology is readily available in all electronic manufacturing facilities [27].

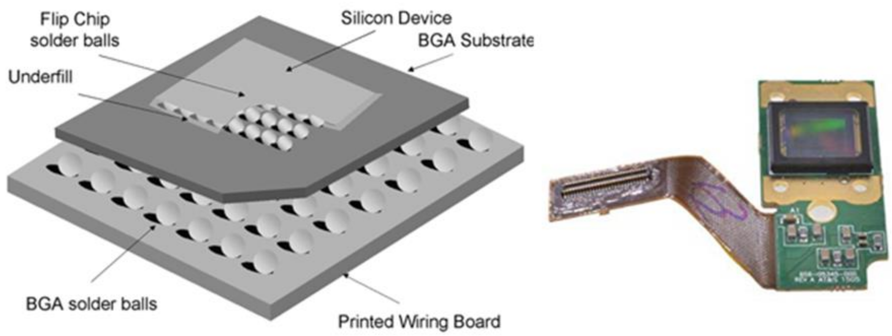


Figure 15 - IBGA packaging.

Bare Die Packaging of an image sensor entails placing the sensor chip directly onto the substrate and then connecting the data channels with a Wire Bond Technology, which is shown in Fig.16. Sensor PCB is first placed into a dispensing system where the bonding agent is dispensed via a nozzle onto a PCB. An image sensor chip is then removed from a wafer via SMT, placed into the right location, and UV cured. The sensor chip then undergoes a thermal cure to finish the bonding process and is transferred to a Wire Bonding cell where a robotic arm stitches every sensor channel with a solder wire to a respective pad location onto the PCB. The main disadvantages of this principle are the size of the package, due to extra wire bonding technique needed, as well as the complexity and cost of the manufacturing equipment. Advantages include best in class optical sensor placement and data bond reliability [28].

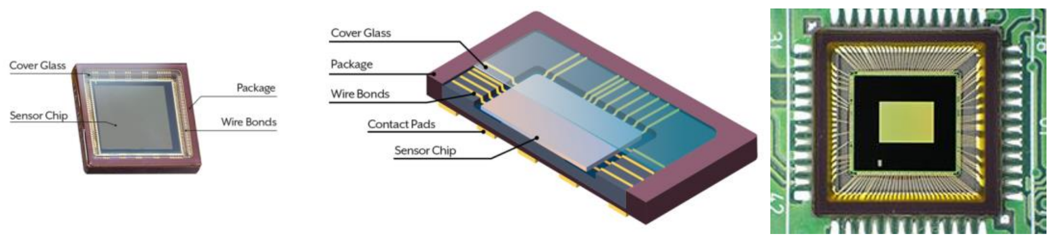


Figure 16 - Packaging for image sensors [22].

Chip-Scale Package is a category of integrated circuit package which is mounted. The surface and its size not more than 1.2 times the size of the original die. Since the introduction of chip-scale packages, they have become one of the biggest trends in the electronics industry [29].

3.2.4.14 <u>Temperature Performance</u>

Temperature performance is a byproduct of automotive operational environment. Contrary to consumer electronics, automotive products must perform at more extreme conditions in a range of different environments. Today’s vehicles are rated to perform in weather conditions between 40DegC to +85DegC, and stationary conditions up to +105DegC.

3.2.4.15 <u>Chief Ray Angle</u>

Chief Ray Angle (CRA) of the image is related to the microlens array placed on top of the image sensor package. The higher the CRA, the smaller the optics can be that focus the light on top of the imager. Cost is also a consideration: there is a price difference between zero CRA imagers and non-zero.

3.2.5 Housing

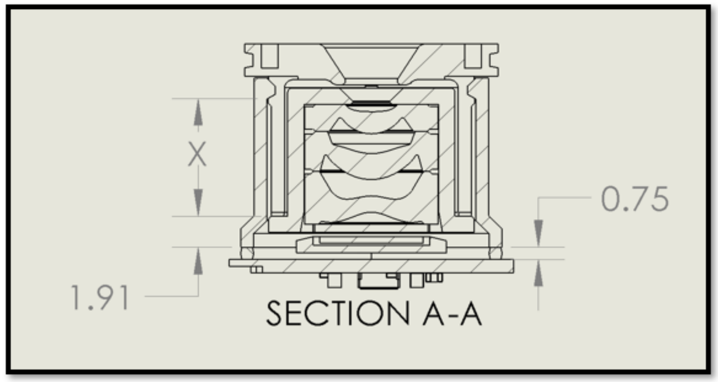
This section describes a lowcost Athermalized lens design which compensates for thermal expansion through the inclusion of a thermal compensation material. Thermal expansion is the tendency of matter to change its shape, area, and volume in response to a change in temperature. In the lens design, a thermal compensation material is integrated into the lens housing so that the lens elements shift with the thermal expansion of the assembly maintaining the correct focal length. Due to the inclusion of the thermal compensation material, the lens elements can be designed with lower-cost materials, such as optical plastic elements. Typically, optical glass is used for lens design to minimize thermal expansion as optical glass has lower thermal expansion than optical plastics. In this case, with the integration of the thermal compensation material in the lens housing, the higher thermal expansion of optical plastic can be compensated. Therefore, the lower-cost plastic element can be used in the design. For an imaging lens assembly, it is important to understand the thermal expansion properties of the materials which construct the assembly. Temperature can affect the focus, image scale, and refractive index of the lens components. This means the optical quality of the lens can be impacted by temperature. Figure 17 demonstrates the impact of focal plane shift due to temperature change of an imaging system.

Chassis Properties:	
Material:	Dynacast B390 Aluminum Alloy
CTE:	0.000018

Glue Bond Properties:	
Material:	Delo DualBond OB786
CTE:	0.000038
Height:	0.00075

Athermalization Spacer Properties:	
Material:	Mitsubishi Chem TIVAR 1000 UHMW-PE
CTE:	0.000198

Assumptions:
Intial state is assumed as 25° C
X is the optimal height of the athermalization spacer from a snap feature on the camera's chassis
The height of the chassis is taken as X + 0.00191
The glue bond between the lens body and the athermalization spacer has 0 thickness
The Materials expand linearly according to the equation: Δlength = CTE*(ΔTemperature)
The Len's focus plane shifts to -95µm in the Hottest Case of 95° C (HOT CASE)
The Len's focus plane shifts to +75µm in the Coldest Case of -40° C (COLD CASE)
As the Len's focus plane shift is not linear, a HOT CASE and COLD CASE calculation will be performed to find the optimum values for the spacer length (X)
A value in between these two calculations will be taken as the optimal athermalization spacer length



HOT CASE	
-0.000095 = (B5*0.00075*70) + (E5*(X+0.00191)*70)-(H5*X*70)	
Optimal Length for HOT CASE in mm:	7.889015873

COLD CASE	
0.000075 = (B5*0.00075*-65) + (E5*(X+0.00191)*-65)-(H5*X*-65)	
Optimal Length for COLD CASE in mm:	6.759589744

Figure 17 - Thermal expansion for a lens.

The change in a lens's refractive index with temperature (described by dn/dT) as well as mechanical element alignment can lead to a shift in the lens's focal length (Δf) – changing the focus position, which is displayed in Fig.17. In the case of automotive advanced driver assistance systems (ADAS) that rely on camera imaging, the functionality of the algorithm depends on the quality of the optics. For this reason, it is important that the lens assembly is designed to be Athermalized where the back focal length shift over temperature of the lens shall be minimized or zero. In the lens design, a thermal compensation material is integrated into the lens housing so that the lens elements shift with the thermal expansion of the assembly maintaining the correct focal length, shown in Fig.18.

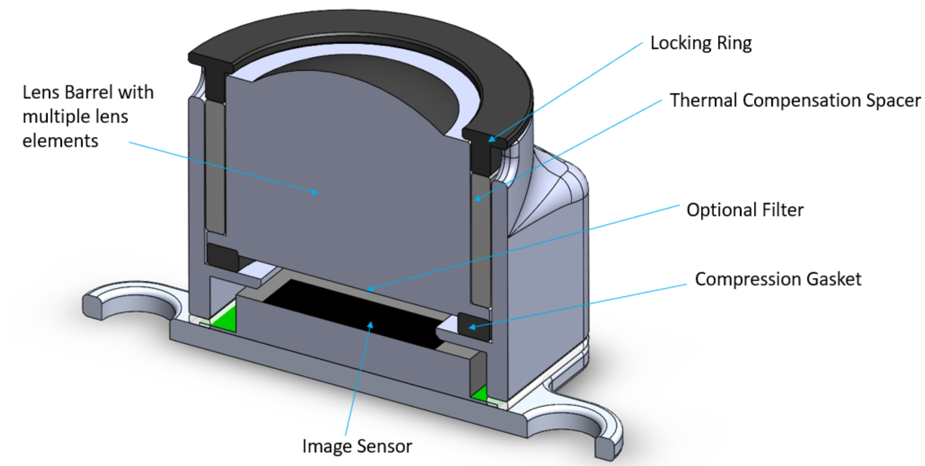


Figure 18 - Lens Design with a call-out to the thermal compensation material

3.2.5.1 Thermal Compensation Material

Material that has a known Coefficient of Thermal Expansion (CTE) and other properties listed below (per selection criteria) has a matched length that equals to EFL shift of the lens barrel assembly. A Thermal Compensation Spacer is added to the assembly so that MTF change due to EFL shift across negative and positive temperatures is less than 1%. Young's Modulus (E) of > 1500 MPa is required. Soft materials are more prone to creep. When stressed within the proportional limit, plastic material shows an initial strain proportional to the modulus of elasticity, followed by a slow but steady increase in strain with time. Note that Higher E materials typically have lower CTE. Heat Deflection Temperature is required to be > 100°C @ 1.8 MPa. Materials that soften at higher temperature tend to creep more at higher temperatures. CTE>100µm/m°C Required for athermalization function. Moisture Absorption at Saturation is required to be < 0.1% for improved dimensional stability. It is important to avoid amorphous polymers, and Crystalline/Semi-Crystalline polymers are needed to be considered as they are more creep resistant.

3.2.5.2 Usage of Plastic Elements for Low Cost

Due to the inclusion of the Thermal Compensation Material the lens elements can be designed with lower-cost materials, such as optical plastic elements. Typically, optical glass is used for lens design to minimize thermal expansion as optical glass has lower thermal expansion than optical plastics. In this case, with the integration of the thermal compensation material in the lens housing the higher thermal expansion of optical plastic can be compensated for. Therefore, the lower-cost plastic element can be used in the design. Resulting function is cost reduction by 40%.

3.2.5.3 Integration of Bandpass Filtration

Depending on the application of the lens assembly, the system may require specified spectral filtration. For example, if the camera application is sensing in infrared or near-infrared wavelengths filtration is necessitated. In this case, a bandpass filter is applied which filters out visible wavelength light in favor of passing through near-infrared and infrared wavelengths. The inclusion of a specified optical filtration in the lens design will reduce unwanted light intrusion and unwanted flare. In the case of a driver monitoring system, visible light wavelengths are not desired and should be filtered out before reaching the imager. By including a bandpass filter in the lens design the risk of intrusive flare light can be mitigated. In the Athermalized lens design, the bandpass filtration necessitated by the camera application can be integrated into the lens assembly.

3.2.6 Lens

Figure 19 gives example of a DMS Lens Assembly requirements.

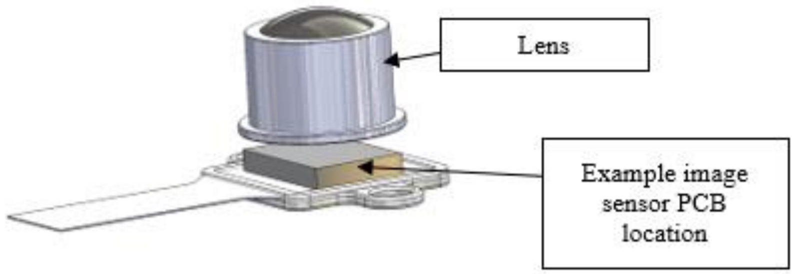


Figure 19 - DMS lens assembly.

Table 4 - DMS lens assembly requirements.

Specification Parameter	LL	UL	Type	SI Unit	Reference
MTF Performance Temperature Range	-40	95	Mechanical	Degrees Celsius	ISO 12233, ISO 1
Storage Temperature	-40	105	Mechanical	Degrees Celsius	ISO 1
Construction	3P* + G** IRF		Mechanical	*plastic lens elements **glass filter	
Operating Wavelength	900	1000	Optical	nm	
Bandpass IR Filter Transmission [300-880nm]	0	0.1	Optical	%	NIST SRM-2035b
Bandpass IR Filter Transmission [880-920nm]	0	0.4	Optical	Slope in nm/%	NIST SRM-2035b
Bandpass IR Filter 50% Transmission Cutoff	890	910	Optical	nm	NIST SRM-2035b
Bandpass IR Filter Transmission [920-1000nm]	90	100	Optical	%	NIST SRM-2035b
IR Filter Location	Back Side*		Mechanical	*Square Shape	
DOF Image Space	5	40	Optical	µm (microns)	
DOF Object Space	650	1000	Optical	mm	
Diagonal FOV	59	63	Optical	Angle Degrees	
F Number	0	2.3	Optical	F#	
Lens assembly max length	0	9	Mechanical	mm	
Distance between front of the lens and imager surface	0	10	Mechanical	mm	
Lens assembly max width	0	11.5	Mechanical	mm	
Distortion	-1.5	1.5	Optical	%	ISO 9039:2008
Distortion Tolerance	-0.5	0.5	Optical	%	ISO 9039:2008
CRA	See Sensor Spec		Optical	Angle Degrees	
Relative Illumination	45	100	Optical	%	ISO 13653:2019

Deviation Between Mech/Opt Axes	0	0.5	Manufacturing	Angle Degrees	ISO 10110-6:2015
MTF Performance On-Axis	65	80	Optical	%	ISO 12233:2017
MTF Performance 0.4FOV	50	80	Optical	%	ISO 12233:2017
MTF Performance 0.8FOV	35	80	Optical	%	ISO 12233:2017
Spatial Frequency	0.25		Optical	Nyquist freq*	ISO 12233:2017 *See sensor spec
IP Rating	IP52		Mechanical		IEC 60529
Gasket Compression for Athermalization	5 (.04)	61 (0.488)	Mechanical	% (mm)	
EFL	5	6	Optical	mm	
AR Coating Reflectivity	0	1	Optical	%	NIST SRM-2036
Stray Light and Halo	See Below		Optical		
Ghost Reflections	See Below		Optical		
Contamination for Particle Size >74µm	0		Manufacturing	Particle count	
Contamination for Particle Size [50-74µm]	0	10	Manufacturing	Particle count	
Contamination for Particle Size [25-50µm]	0	30	Manufacturing	Particle count	

3.2.6.1 MTF Performance Temperature Range

The lens assembly shall have an Athermalized design, i.e., the BFL-shift over temperature of the lens barrel shall be matched by the lens holder so that the difference in positions of the best optical image plane and the sensor plane is minimized (the goal is zero difference). The MTF sharpness of the camera lens shall hold across the temperature range of -40 - 95° C. Note the lens requirements are higher than camera requirements. Requirements for MTF Performance limits are shown in the table. MTF measurements are to be compliant to ISO12233 [30] with measurements On-Axis, at 40% Field of View, and 80% Field of View.

3.2.6.2 Storage Temperature

The lens assembly shall be designed to survive storage between a minimum temperature -40°C to a maximum temperature of +105°C for 24hrs. Lens assembly is subject to complete functional test defined by DMS Measurement Agreement sheet following exposure to storage temperature as well as subject to visual inspection.

3.2.6.3 Construction

The lens barrel material is to be A6061 (black). The design shall include a lens gasket for the purpose of fixing the lens into place and sealing with a ridged area between the lens barrel and housing. Construction material agreement with customer.

3.2.6.4 Operating Wavelength

The operating wavelength shall be 900-1000nm with a centroid wavelength at 945nm +/-5nm. This requirement includes the whole optical path including the camera sensor selection. Note the application LED bins for spectral output are described by a table below. The Operating wavelength shall be validated through the qualification testing.

Table 5 - Wavelength peaks for each BIN.

BIN	Peak Wavelength (nm)	
	MINIMUM	MAXIMUM
1	935	940
2	940	945
3	945	950
4	950	955

3.2.6.5 IR Band Pass Filter

There should be a bandpass filter of 900-1000nm. The bandpass filter shall be placed at the back of the lens. The bandpass filter shall be of ≥ OD3 (Optical Density) in the visible region up to 880nm, with transmission less than 0.1% (maximum). Wavelengths beyond this optical density will be passed through. The bandpass IR Filter transmission beyond 880 nm shall be characterized by [880-920] nm transmission with a slope of ≤0.4 (nm/%), the 50% transmission cutoff between [890-910] nm, and by transmission from [920-1000] nm ≥90%. This requirement shall be fulfilled for the whole service life. Filter specification is valid for all relevant angles. Transmission is to be measured in production at the batch level. The transmission measurement system shall be performed with a spectrometer sensitive to the appropriate NIR wavelengths. The spectrometer shall be calibrated to NIST SRM-2035b [31] standard for NIR Wavelength Transmission standard.

3.2.6.6 Depth of Focus (DOF)

The DOF On-Axis of the lens shall have a range of 5-40μm tolerance of the placement of the image plane in relation to the lens. Reference requirement for On-Axis MTF test limits.

3.2.6.7 Field of View (FOV)

The vertical field of view shall be 37.5 degrees +/- 2.5 tolerance. The horizontal field of view shall be 50 degrees +/- 1 tolerance. The diagonal field of view shall be 61 +/- 2 degrees tolerance. The entire sensor area is 1280x960 pixels with 3.75μm pitch, or 4.8mm x 3.6mm. The Field of View of the lens shall be measured in production at the batch level. Field of View measurements consider the sensor specification for accurate measurement of the field angle.

3.2.6.8 F-Number

The nominal f-number shall be within the range specified in Section 3.2 Performance Test Limit Table. The f-number of the lens shall be measured in production at the batch level. The f-number is a measure of the ratio of the focal length to the diameter of the entrance pupil.

3.2.6.9 Total Lens Barrel Length

The length of the lens barrel from the front surface of the lens to the back surface of the lens. Caliper measurement is required for validation of requirement fulfillment.

3.2.6.10 Lens Distortion

The nominal lens distortion requirement shall be less than +/- 6.0% (d), such that the pixel sampling (pixels/degree) is relatively uniform across the image. The max tolerance for the lens distortion is 0.5% of the initial value given above (d). The distortion of the lens shall be measured in production at the batch level. The distortion measurement method shall be compliant to ISO 9039:2008 – Quality evaluation of optical systems – determination of distortion.

3.2.6.11 Chief Ray Angle (CRA)

The lens shall have a Chief Ray Angle of angle value less than 9.5 degrees. This parameter shall be verified during the design verification stage. CRA can be verified through measurement of off-axis collimated light passing through the lens, CRA can be calculated from the lateral movements of the focused light on the image plane.

3.2.6.12 Relative Illumination

Relative illumination, defined as the ratio between the brightness of the image corners and the image center as measured by the image sensor, shall be ≥60%. This parameter shall be verified during design verification stage. Relative illumination of the lens optics shall be measured following ISO 13653:2019 [32].

3.2.6.13 Optical Axis Deviation

Misalignment between the optical axis and the mechanical axis will be smaller than 0.5º. The decenter between the optical axis intersection and the optomechanical axis intersection with the image plane shall be less than 46 µm. Over its lifetime (including change with temperature), the optical axis must remain stable to within 0.5º from the initial value. The optical axis deviation shall be measured in production at the batch level. The optical axis of the lens assembly shall be verified in accordance to ISO 10110-6:2015 [33].

3.2.6.14 Barrel Mechanical Parameters and Threading

The lens barrel shall be in an M12 barrel with M12x0.5g threading pitch size. The barrel thread shall be at least 4mm. The barrel mechanical parameters and threading shall be verified during the design verification stage.

3.2.6.15 Modulation Transfer Function (MTF)

MTF stands for Modulus of the Transfer Function, also known as Spatial Frequency Response (SFR). This is simply a measure of resolution/sharpness of the optics. The table below gives the MTF requirements for 50-line pairs per millimeter (lp/mm) for the lens only (infinite object distance). Both tangential MTF and radial (sagittal) MTF shall be above requirements listed in the performance specification table. MTF requirements are for a Nyquist frequency of 50 lp/mm. The MTF performance of the lens assembly shall hold for the lifetime of the system. MTF shall be measured in production at the batch level. The MTF of the lens assembly shall be measured in accordance to ISO-12233:2017 [30].

3.2.6.16 IP Rating

The IP rating specifies and classifies the degree of protection provided by mechanical casing and enclosures. In this case, the IP rating refers to just the lens assembly. IP rating shall be classified in accordance with IEC standard 60529 [34].

3.2.6.17 Gasket Compress for Best Focus

The best focus for the lens occurs at the level of compression defined in 3.2 Performance Test Limits (Table 7). The gasket compression shall be measured with calipers and/or with a torque gauge.

3.2.6.18 EFL

The Effective Focal Length (EFL) of the lens shall be within 5 – 6 mm. The EFL determines the magnification of the lens, which in turn defines the image size. Variables/Factors such as sensor size, packaging limitations, and focus distance requirements shall dictate the EFL of the lens assembly. EFL shall be measured in production at the batch level. EFL can be measured by measuring the magnification of a target with the measurements calibrated to a master lens.

3.2.6.19 AR Coating Reflectivity

Coatings are additions to the mold surface. Common coatings used in optics are vapor-deposited thin films. The Anti-Reflective (AR) coating shall have a reflectivity of less than 1%

for every optical surface for all relevant angles for any wavelength within the range, where IR cut-off is defined as the cut-on and cut-off, respectively. This requirement shall be fulfilled for the whole service life. The durability of the coatings shall be proven during the qualification stage and neither cracking nor adhesion failure is acceptable. The reflectivity of the AR coating shall be measured in production at batch and shall be measured with a spectrometer calibrated to NIST SRM-2036 [35].

3.2.6.20 Stray Light/ Halo

The optical path of the camera and lens shall have no visible light passing beyond the IR filter in order to avoid all instances of stray light. The following Fig.20 provides an example of the appearance of stray light in the end image output.

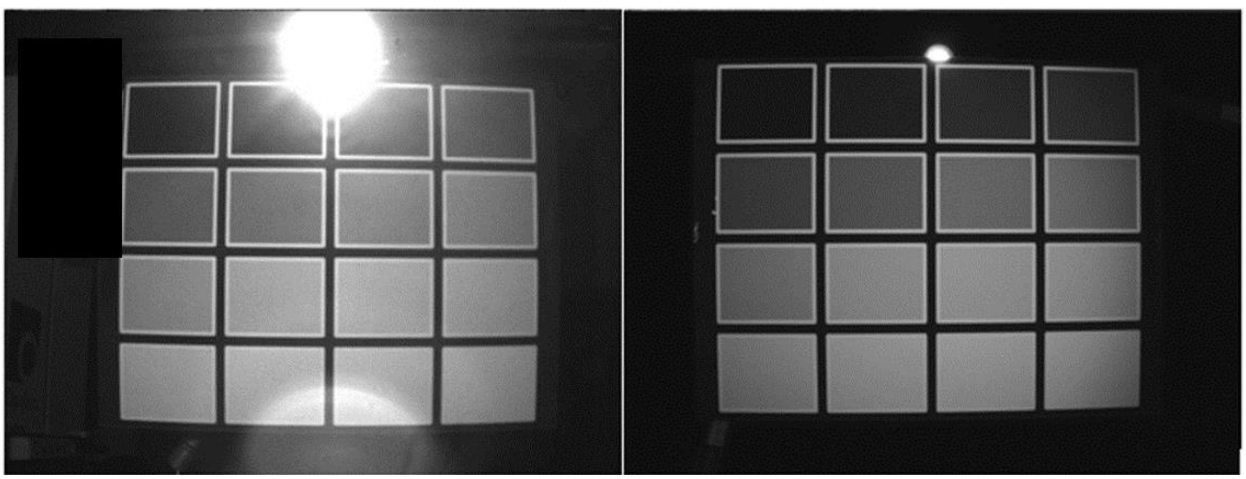


Figure 20 - Example of stray light in camera optical path and stray light mitigation.

3.2.6.21 Ghost Reflections

Ghost reflection (shown in Fig.20) requirement on the lens assembly are:

- No unwanted internal reflection artifacts (ghost images) can have intensities larger than 20 ppm of the max value of the image of the light source.
- For ghost images closer than 100 µm to the image center of the light source, the max ghost intensity shall be < 0.1 % of the max value of the image of the light source

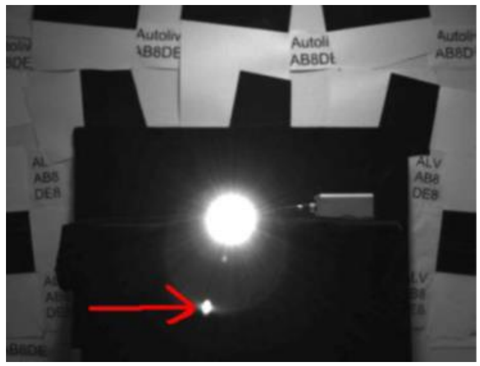


Figure 21 - Image showing a ghost reflection. The camera is looking into a fiber light source.

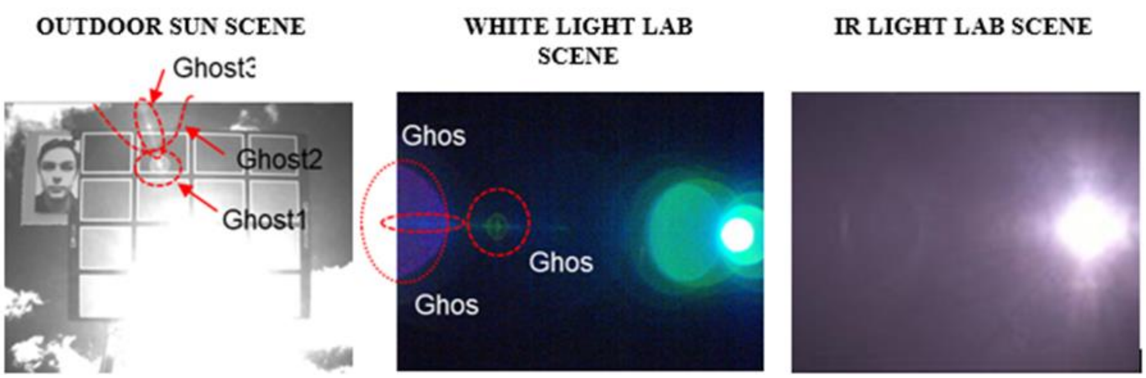


Figure 22 - Examples of the visibility of Ghost Reflections during testing environments

The measurement equipment used to characterize ghost reflections on the lens assembly shall be the same as described EFL requirement. The Pass/Fail limits shall be agreed by the manufacturer and lens supplier using corner samples (boundary samples) shipped to the customer in advance of the starting mass production.

3.2.6.22 Contamination

Two types of defects are specified in this requirement, localized imperfections and long scratches, and they shall apply to both the glass surfaces and their coatings in the optical assembly. Localized surface imperfections to not exceed 15/2x0.2, and long scratches to not exceed 15/L2x0.04. Note that EFL is of a higher priority and thus shall take precedence during testing. For the external exposed surfaces (especially those facing the image sensor, i.e., the rear of lens stack and lens assembly), proper cleaning steps must be part of the production process to ensure that particles do not exceed the values in Table.6.

Table 6 - Contamination requirements.

Particle size	Maximum allowed particles
>74µm	0
50<x<74µm	<10 particles
25<x<50µm	<30 particles

3.2.6.23 Particle allowance on external surface.

The particle contamination shall be verified in production at the batch level through visual inspection. Measurement of particles shall be made using a microscope and reference scale.

3.2.6.24 Environment

3.2.6.24.1 Product Delivery Cleanliness

Lenses shall be produced and packaged in a clean-room environment better than or equal to ISO 6 [36] [9]. Lenses shall be delivered in an ESD-proof tray. The tray and mating cover shall be sealed with one or more plastic bags (vacuum) protecting from dust and humidity. Actual dimensions of the tray shall be agreed upon between the lens assembly supplier and customer. It must also be guaranteed that no wear occurs between the lens and packaging material that can generate particles during transport.

3.2.6.24.2 Qualification & Classification

The lens shall withstand all tests agreed in the customer-specific Qualification Test Plan.

3.2.6.24.3 Service Life and Driving Profile

The qualification plan is designed based upon a service life and driving profile of 17 years or 340,000 km of mileage (800hrs/year of operating time). Service life shall be tested by accelerated tests according to the qualification plan. Requirements in Chapter 3 shall be fulfilled over ptoduct's lifetime.

3.2.6.24.4 Climate Compatibility

The lens shall be designed for an ambient operating temperature of Tmin -40°C to Tmax +95°C, surviving storage in Tmin -40°C to Tmax +105°C for 24hrs.The temperature spectrum used is defined as shown in Fig.23.

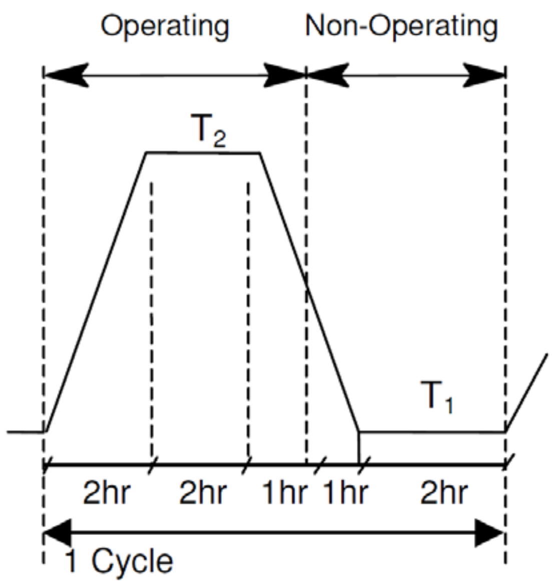


Figure 23 - Powered Thermal Cycle Profile

The lens shall withstand climatic tests for Damp Heat Cycle Test & Damp Heat Steady State Test. With these tests, the maximum relative humidity is >95%, and the lens shall withstand High Temperature High Humidity for 1000hours cycles at 85°C and 85% relative humidity. The lens shall show no signs of corrosion after qualification tests on visible surfaces.

3.2.6.25 Chemical Compatibility

The lens shall withstand chemical tests as defined in customer-specific requirements.

3.2.6.26 Mechanical Durability

The lens shall withstand mechanical tests (vibration/shock) as defined in customer-specific requirements.

3.2.7 Front Filter

The Front Filter of the DMS sits in front of both the camera lens assembly and illuminating IR LEDs (referred to as camera system). The functionality of the Front Filter is to both obscure the driver's view of the camera system & to perform filtration, which allows the camera system to function. The optomechanical requirements of the DMS Front Filter are given both in this PTS and in the accompanying drawing, which together forms the complete specification.

3.2.7.1 Configuration

Figure 24 gives an example of a DMS Front Filter where the area of coverage in front of the camera lens assembly & LED Light source is considered optically critical. Optically critical means that the Front Filter will be held to the specified optical requirements defined in this PTS, which allow for the Front Filter to not impede upon the camera system functionality.

3.2.7.2 Optical ROI Definition:

As displayed in Fig.24, the front and back surfaces of the material that are within the diagonal field of view of the optic, whether it's a light source, light sensor, or lens.

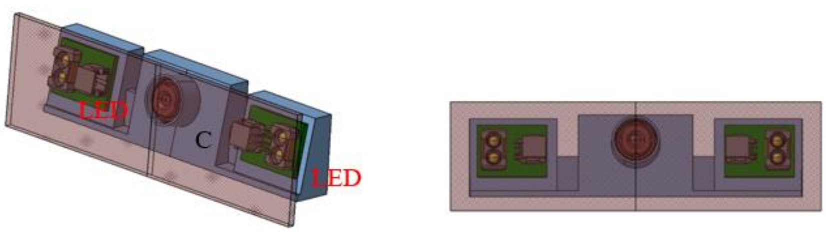


Figure 24 - DMS camera system highlighting Optically Critical surfaces

Table 7 - Performance Test Limits Table.

Specification Parameter	LL	UL	Type	Reference	Proposed Measurement Instrument
Coefficient of Thermal Expansion (x10^-6/DegC)	0	65	Mechanical	ISO 11359-2 [37]	Mold Pellet Spec Sheet
Mold Operating Humidity Range	0	100	Mechanical	ISO 558 [38]	Mold Pellet Spec Sheet
Operating Temperature (DegC)	-40	105	Mechanical	ISO 1 [39]	Thermometer

Optical ROI Flatness (mm)	-0.05	0.05	Mechanical		Zygo Interferometer/ Surface Profiler
Surface Roughness Ra (µm)	0.012	0	Mechanical	ISO 4287-1 [40]	Zygo Interferometer/ Surface Profiler
Optical ROI Thickness (mm)	1	3	Mechanical		Calipers
Water Absorption 24hr immersion (%)	0	0.02	Mechanical	ISO 62 [41]	Mold Pellet Spec Sheet
Abbe Number	50	70	Optical	ISO 12123 [42]	Mold Pellet Spec Sheet
Birefringence (0/10) with BK7 being 1	0	2	Optical	ISO 11455 [43]	Mold Pellet Spec Sheet
Change in refractive index with temperature (dn/dt) (10^-6/DegC)	-102	4	Optical	ISO 489 [44]	Mold Pellet Spec Sheet
Color (Black) Application Specific	[0,0,0]	$\Delta E_{ab} < 2.3$	Optical	ISO/CIE 11664-5 [45]	Colorimeter
Index of Refraction	1.45	1.55	Optical	ISO 489 [44]	Mold Pellet Spec Sheet
Optical Flatness-Irregularity (Fringes/mm)	2	0	Optical	ASTM D637 – 90 [46]	Zygo Interferometer/ Surface Profiler
MTF Degradation	0	4%	Optical	ISO 12233 [30]	DMSFocus Software
Transmission >900 nm (%)	90	100	Optical	ISO 12123 [42]	Ocean Optics USB4000 Spectrometer
Transmission 450-850 nm %	0	1	Optical	ISO 12123 [42]	Ocean Optics USB4000 Spectrometer
Transmission 850-900 nm 50% Slope	0.5	1	Optical	ISO 12123 [42]	Ocean Optics USB4000 Spectrometer
Vapor Deposition AR Coating Reflectivity @900-1000nm back (GU)	0	10	Optical	ASTM D523 - 14 (60Degree) [47]	ETB-0686 Gloss Meter
Vapor Deposition R Coating Reflectivity @900-1000nm front (GU)	70	100	Optical	ASTM D523 - 14 (60Degree) [47]	ETB-0686 Gloss Meter
Resistance to Fade (Accelerated Xenon Weathering) (kJ/m^2)	1505	NA	Mechanical	SAE J2412 [48]	Lux Meter

Table 8 - General Tolerance Limits for Molded Plastics Table.

Typical Cost Drivers and Tolerance Limits for Injection Molded Optics			
Attribute	**Low Cost ------> High Cost**		
Focal Length (%)	±5	±2	±0.5
Radius of Curvature (%)	±5	±2	±0.5
Power (Fringes)	10	5	1
Irregularity (Fringes/10mm)	4	2	1
Scratch/Dig	80/50	60/40	40/20
Center Thickness (mm)	±0.1	±0.05	±0.01
Flange Diameter (mm)	±0.1	±0.05	±0.01
Concentricity (mm)	0.1	0.05	0.025
Center-to-Edge Thickness Ratio	1:1	3:1	5:1
Surface Roughness (Arms)	>75	60	40

3.2.7.3 Operating Humidity Range

The Operating Humidity Range is the expected environment condition in which the product will be operated. A Hygrometer shall be used for humidity measurements. Considerations need to be taken into account when material is selected that any internal and external automotive instruments will be exposed to the maximum amount of humidity.

3.2.7.4 Operating Temperature

A Thermometer shall be used to measure temperature. Considerations need to be taken when material is selected, to make sure that material conforms to automotive material temperature requirements. OEM requirement overrides temperature range specified by this document unless OEM specification is less than defined by the specification table of this document.

3.2.7.5 Optical ROI Flatness

Tolerance for the flatness of the Optical Region of Interest on the filter surface. Tolerance for the flatness of the Optical Region of Interest on the filter surface. This applies to the mold surface only.

3.2.7.6 Surface Roughness

Surface roughness is a component of surface texture. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. In surface metrology, roughness is typically considered to be the high-frequency, short-wavelength component of a measured surface. This metrology applies only to the surface of the end molded surface. Surface shall be inspected by a Surface Profilometer, such as an Interferometer. The proposed instrument is defined within the requirements table in Tab.9.

Table 9 - Surface profilometry requirements.

Finish	SPI* standard	Finishing Method	Typical surface roughness Ra (µm)	MTF Loss
Optical Filter Grade	NA	NA	<0.012	<1%
Super High Glossy finish	A-1	Grade #3, 6000 Grit Diamond Buff	0.012 to 0.025	
High Glossy finish	A-2	Grade #6, 3000 Grit Diamond Buff	0.025 to 0.05	
Normal Glossy finish	A-3	Grade #15, 1200 Grit Diamond Buff	0.05 to 0.10	
Fine Semi-glossy finish	B-1	600 Grit Paper	0.05 to 0.10	
Medium Semi-glossy finish	B-2	400 Grit Paper	0.10 to 0.15	
Normal Semi-glossy finish	B-3	320 Grit Paper	0.28 to 0.32	
Fine Matte finish	C-1	600 Grit Stone	0.35 to 0.40	
Medium Matte finish	C-2	400 Grit Stone	0.45 to 0.55	
Normal Matte finish	C-3	320 Grit Stone	0.63 to 0.70	

Satin Textured finish	D-1	Dry Blast Glass Bead #11	0.80 to 1.00	
Dull Textured finish	D-2	Dry Blast #240 Oxide	1.00 to 2.80	
Rough Textured finish	D-3	Dry Blast #24 Oxide	3.20 to 18.0	
As machined	-	Finished to the machinist's discretion	3.20 (with visible machining marks)	

3.2.7.7 Thickness

Thickness refers to front optical ROI material thickness. Since there is a tradeoff between the amount of pigmentation available to be placed inside the material, optical properties and strength of the molded surface, special considerations need to be taken in to account when defining the mechanical thickness of the filter. The thinner the filter, the better optical properties, however, strength and optical density due to pigmentation are affected.

3.2.7.8 Water Absorption

Moisture absorption (also known as water absorption) is the capacity of a material to absorb moisture from its environment. Plastics absorb water to a limited degree. The degree of moisture absorption depends on the type of plastic and the ambient conditions such as temperature, humidity and contact time. Not only can dimensions change due to moisture absorption, but also material properties, such as mechanical strength, electrical conductivity and the dielectric loss factor, can also be affected. Polyamides (nylons) generally show higher water absorption than other engineering plastics. This leads to dimensional changes to finished parts, a reduction in strength, and to changes in electrical insulating characteristics. Material will contract and expand based upon water absorption properties, therefore it is important to maintain low water absorption requirements to meet mechanical tolerancing.

3.2.7.9 Abbe Number

In optics and lens design, the Abbe number, also known as the V-number or a measure of dispersion of a transparent material (variation of refractive index versus wavelength), with high values of V indicating low dispersion. Abbe number shall be procured from the pallet material datasheet.

3.2.7.10 Birefringence

An anisotropy of refractive index in optically homogeneous and isotropic glasses, usually induced by mechanical and/or thermal stress. The refractive index depends on the orientation of the plane of polarization and the propagation vector of the electromagnetic wave with respect to the axis of the principal stresses. Birefringence shall be procured from the material supplier. Since measurement of birefringence is subjective, special care shall be taken into consideration when selecting a material. N-BK7 shall be used as a reference material for relative measure of birefringence.

3.2.7.11 Change in refractive index with temperature dn/dT

Dn/dT is a property of a material change in refractive index of glass with temperature. It signifies optical stability of the material over a range of temperatures. This parameter shall be procured in accordance to the material datasheet.

3.2.7.12 Color

Color refers to the CIE color code specification of the material. Color shall be procured from the OEM requirement and extrapolated/confirmed to end molded material testing during safe launch activity. Limits of color shall be defined by the OEM. The expectation is that the color shall have a color difference of less than the Just Noticeable Difference (JND = 2.3) from what is defined by the OEM.

3.2.7.13 Index of Refraction

The index of refraction is defined as the speed of light in vacuum divided by the speed of light in the medium. Index of refraction shall be procured from the material specification datasheet. NBK7 is used for reference as a common optical material.

3.2.7.14 Optical Flatness-Irregularity

This is an alternative definition of mechanical flatness. An interferometer may be used to measure flatness of the optical ROI.

3.2.7.15 MTF Degradation

MTF stands for Modulus of the Transfer Function, also known as Spatial Frequency Response (SFR). This is simply a measure of resolution/sharpness of the optics. MTF degradation is the overall performance metric of how the plastic mold affects the overall DMS camera system. 4% refers to 0.03 MTF points with 0.00 being the minima, and 0.80 (or 80%) being the maxima. MTF (SFR) shall be measured using ISO specification for slanted edge method, measured at spatial frequency defined by Optical Test Definitions Document. This parameter shall be extrapolated by internal testing of the final optical assembly.

3.2.7.16 Transmission

Optical transmission is a measure of what proportion of light is transmitted through a turbid medium. Light may be attenuated due to absorption in the medium, or it may be scattered out of the beam. Transmission is wavelength specific and ultimately is the definition of an optical filter. Transmission for a long path filter shall be defined in three segments (no pass, transition rise slope, and pass). Special considerations need to be taken into account when selecting material pigmentation. The sharper the slope (transition), the more versatile and precise the filter is.

3.2.7.17 Coatings

Coatings are additions to the mold surface. Common coatings used in optics are vapor-deposited thin films. Special care needs to be considered when selecting a coating. The reflective coatings shall allow for material to appear shinier. However, they also effect the index or refraction, transmission, haze and dispersion of the overall filter assembly. Anti-reflective coating shall be used with care to prevent internal reflections of light for camera assemblies with internal light sources. Material gloss is defined in Gloss Units (GU) 60Degree Gloss Meter shall be used to define all non-mirrored surfaces with requirements as shown in Tab.10. 20 Degree Gloss Meter shall be used for all mirrored surfaces.

Table 10 - Gloss range requirements.

Gloss Range with 60° Gloss Meter	**Measure With:**
Mirror Surface > 100 GU	20 °
If Semi-Gloss - 10 to 70 GU	60 °
If High Gloss > 70 GU	20 °
If Low Gloss < 10 GU	85 °

3.2.7.18 Resistance to fade

Resistance to fade shall be defined as visible changes in the material after exposure to extreme sunlight. SAE standard limits for severe Class 4 exposure shall be used. OEM exposure testing shall overrule definitions contained within this document.

3.2.7.19 Environment

Operating and storage environment should accommodate a temperature range between -40C to 105C and humidity range of 0-100%. Product delivery cleanliness should accommodate surface and air cleanliness levels per ISO 8/ ISO 14644 [36].

4 Chapter 4 – Measurement Methods

4.1 Lab MTF at Room Temperature

The purpose of MTF testing is to verify that a product meets initial focus requirements with the setup shown in Fig.25.

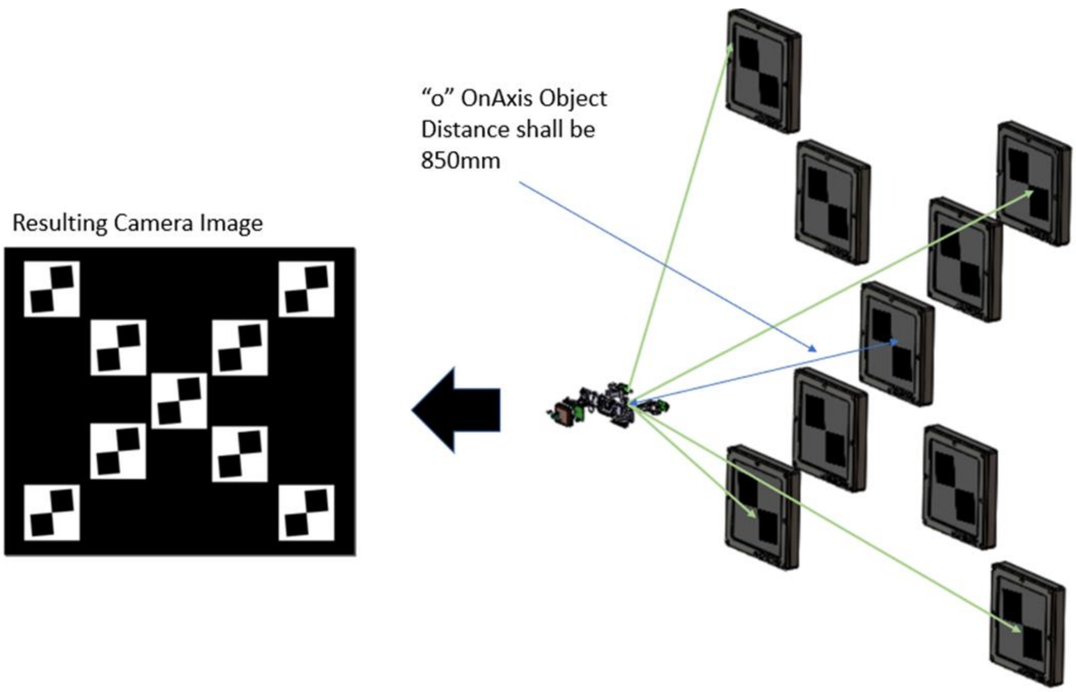


Figure 25 - MTF measurement setup.

In an Edge-Based MTF Measurement, a system's spatial resolution performance can be derived from the MTF (Modulation Transfer Function) plot. It is also sometimes called Edge Spatial Frequency Response. (E-SFR) The Edge-based MTF is measured preferably using the slanted edge method because it produces a good approximation to the MTF of the two-dimensional PSF (Point Spread Function) of the camera/lens system in the direction perpendicular to the edge. This method is performed by analyzing a captured image of a test chart as shown in Fig.26. The analysis is done using specific software. The test chart was designed with a 5^{o} rotation angle.

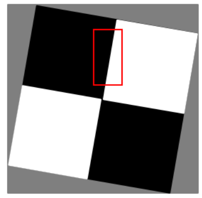


Figure 26 - Test chart used to analyze the MTF

Steps to measure the edge-based MTF or E-SFR is shown in Fig.27

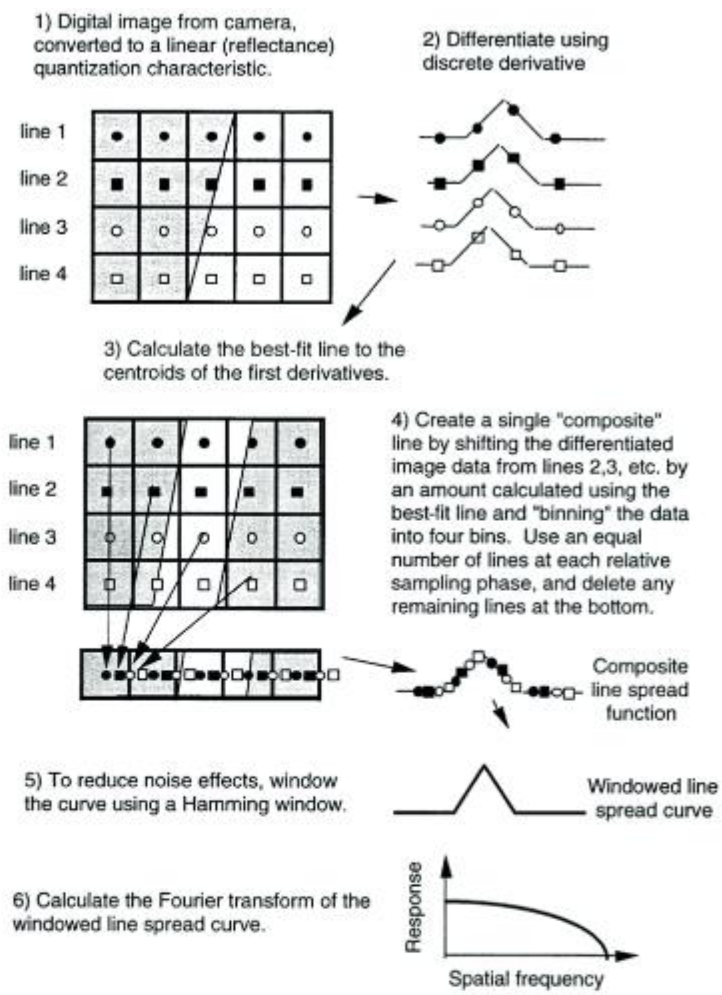


Figure 27 - Steps for measuring the MTF of a camera.

4.1.1 Selection of region of interest (ROI):

In this step, the user selects the region, which includes the slanted edge (on the photo taken by the camera from the test chart). This selected area has "r" rows and "p" pixels.

4.1.2 Point to Line to Edge:

It is very hard to obtain the Point Spread Function (PSF) of a camera/lens system, just by capturing a single point, because of the size and intensity of the target, is too faint and with a lot of noise. Assuming that the imaging system is linear, a number of stars, which are very close together, can be imaged, in order to increase the intensity and get rid of the noise. A better idea would be to capture a few lines of adjacent stars in order to create a white edge against a dark background.

4.1.3 From Digital values to Edge Spread Function (ESF):

The ROI is now converted to an image of the intensities along the edge via the Optoelectronic conversion function (OECF) and Chroma coefficients (a, b, c, etc.), as shown in Eq.2. Each row of the image estimated the ESF of the camera.

$$\varphi(p,r) = a\ OECF[DN_{Chroma\ A}] + b\ OECF[DN_{Chroma\ B}] + c\ OECF[DN_{Chroma\ C}] \qquad (2)$$

DN is the digital output level (0-255).

(p,r) is the index of each pixel, where "r" are rows and "p" are pixels.

for RGB and RCC images Chroma A, B, and C values are defined differently for Eq.2.

4.1.4 From ESF to Line Spread Function (LSF):

ESF for each row is then discretely differentiated to form the discrete LSF (Line Spread Function), (shown in Fig.27, as step 2). The centroid for the LSF of each row is then found along variable x, while x has a range 1 to X. See Eq.3.

$$C(r) = \frac{\sum_{p=1}^{P-1} p[\varphi(p+1,r)-\varphi(p,r)]}{\sum_{p=1}^{P-1}[\varphi(p+1,r)-\varphi(p,r)]} \tag{3}$$

The best-fit line through each of these centroids is calculated, and the slope is computed using Eq.5 (shown in Fig.27, as step 3).

$$m = \overline{\left[\frac{\Delta C(r)}{\Delta r}\right]} \tag{4}$$

The slope of this line is useful to calculate the shift (Eq.6) applied to each row in order to bring each ESF to coincidence around a mutual origin (shown in Fig.27, as step 4).

$$S = \frac{{}^{R}/_{2} - r}{m} \tag{5}$$

4.1.5 Supersampling

Supersampling is a process of sampling of an image at a higher frequency at the target sampling frequency, followed by an averaging down to the true pixel size value. The averaged value has more details about the image taken than the image taken at the camera resolution. This method is used for removing aliasing. If the supersampling process is performed, it shall be done as the 4th step as in the methodology steps. This step creates a re-quantized ESF over a discrete variable “j”, which “j” is 4 times more sampled than “p.” This means the supersampling factor is 4, detailing that 4PX bins are created while each have a width of ¼ of “P” and the averaging is carried out (Eq.5).

$$ESF(j) = \frac{\sum_{r=1}^{R}\sum_{p=1}^{P}\varphi(p,r).\alpha(p,r,j)}{\sum_{p=1}^{P}\alpha(p,r,j)} \tag{6}$$

Where "α" is a counting function, it also decides to exclude or include a value in a bin, Eq.7.

$$\begin{cases} 1 - 0.125 \leq [p - S(r) - j] \\ 0 \qquad\qquad Elsewhere \end{cases} \tag{7}$$

The average Supersampled ESF is differentiated and windowed which yields the LSF(Eq.7). It is noteworthy that the calculation of the first and last values of the LSF is repeated which gives the length of 4P[4X].

$$L\acute{S}F_j = W(j)\frac{ES\acute{F}(j+1) - ES\acute{F}(j-1)}{2}, j = 2, \dots, N-1 \tag{8}$$

Where

$$W(j) = 0.54 + 0.46\cos[\frac{2\pi(j-2X)}{4X}] \tag{9}$$

4.1.6 <u>Discrete Fourier Transform</u>

The final step is to take the Discrete Fourier Transform of the windowed LSF, which is done by substituting the results from step into Eq.10 and then taking the modulus of the result, which gives us the MTF (or e-SFR(f), f=k/X).

$$MTF(f) = D(k)\left|\frac{\sum_{j=1}^{N} LS\acute{F}_W(j)e^{-\frac{i2\pi jk}{N}}}{\sum_{j=1}^{N} LS\acute{F}_W(j)}\right|, for\ k = 0,1 \dots, \frac{N}{2}\ or\ \frac{N+1}{2}\ for\ odd\ N \tag{10}$$

4.1.7 <u>Calculate MTF</u>

To calculate the MTF of the system, images were taken from the test charts at a rate of 30 frames/sec, in 4 different ROIs per BOX, as shown in Fig.28.

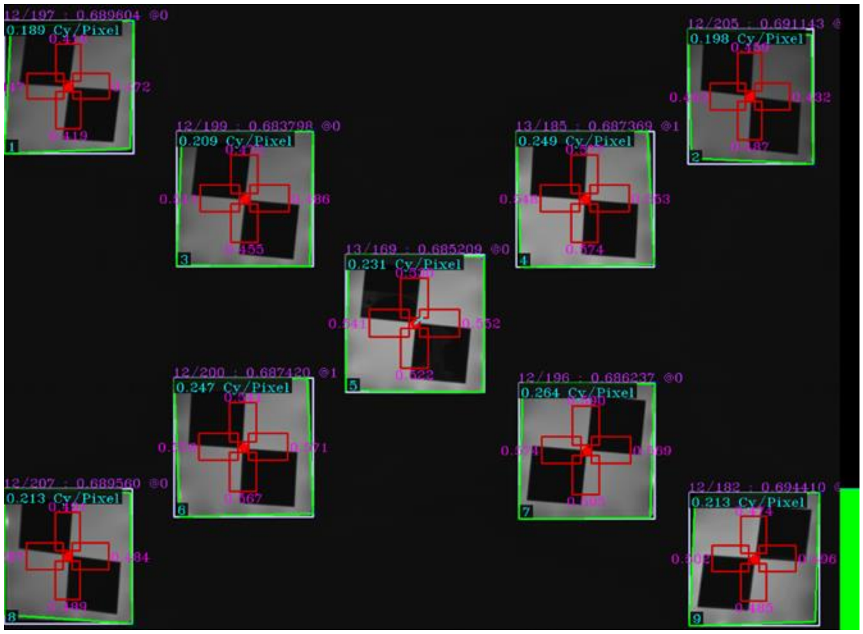


Figure 28 - Position of each box on the MTF target.

For each BOX an MTF is calculated and is averaged over 30 frames as shown in Eq.11.

$$MTF = \frac{MTF_1 + MTF_2 + MTF_3 + MTF_4}{30} \tag{11}$$

The MTF is then averaged on all the test charts and plotted vs spatial frequency, which is normalized by the zero-frequency value. The MTF is measured from 0 to 0.8 (it idealistically [diffraction limited] goes from 0 to 1). The MTF is measured from 0 spatial frequency to 1/4th of the Nyquist frequency. For example, if there is a camera sensor with dimensions of 1280*960 pixels, this yields 1600 pixels diagonal dimension. This means that the sensor has 800 lp (line pairs) radially. If we multiply the pixel pitch (we have from the spec sheet of the sensor) which is 3.75 *10^{-3}mm, by 800 radial line-pairs, we find out that the radius of the sensor is 6mm. when we divide the radial line-pairs by the radius of the sensor we get the Nyquist Frequency to be 133.3 lp/mm. The Flowchart of the MTF measurement algorithm is shown in Figure 29.

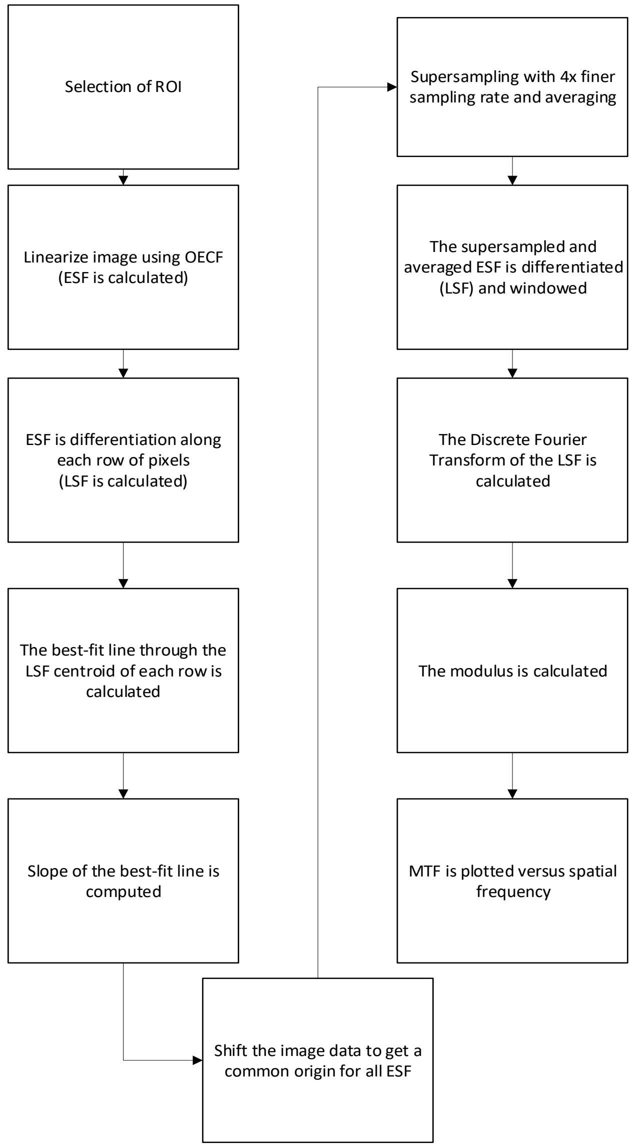


Figure 29 - Flowchart for measuring the MTF algorithm.

We also must correct the MTF for the bias introduced by the discrete derivative FIR filter, which is done by frequency-by-frequency multiplication by the reciprocal "sinc" function. Field Of view: There are 3 different fields of view available on the test chart as shown in Fig.30, that help measure the MTF also for different FOVs.

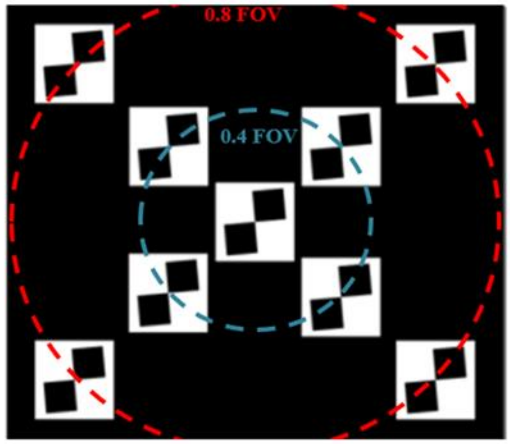


Figure 30 - Different FOVs on the test chart.

4.2 **Lab Distortion at Room Temperature**

Distortion is an optical aberration that shows how the magnification in an image across the field of varies at a fixed distance. It is noteworthy that distortion is a monochromatic aberration. Distortion is different for different wavelengths, meaning that while calibrating a machine vision system, like a camera, the illuminating wavelength must be taken into account. Distortion is calculated by using Eq.12. which is typically specified as a percentage of the field height as displayed in Fig.31.

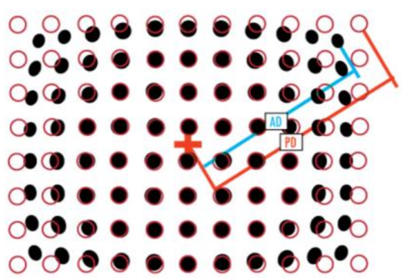


Figure 31 - Calibrated Target vs. Imaged Dot Distortion Pattern.

$$Distortion = \left(\frac{AD-PD}{PD}\right) * 100\% \tag{12}$$

where AD is the Actual Distance and PD is Predicted Distance as shown in Fig.32.

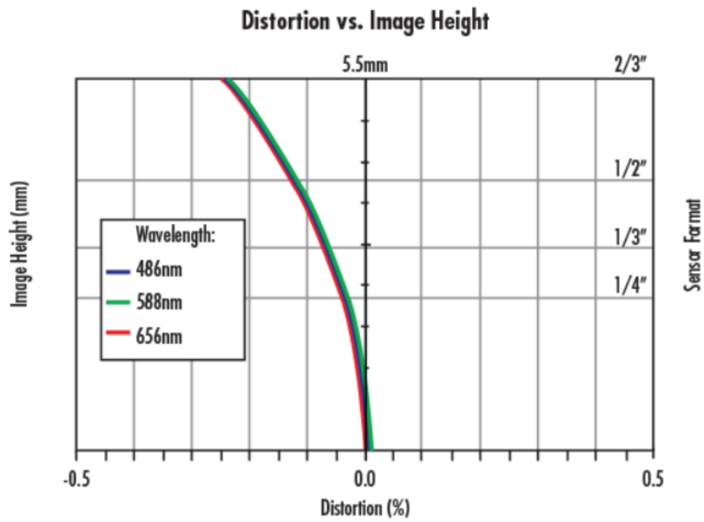


Figure 32 - Example of distortion graph.

In Eq.13 the radial transfer function is shown which the distortion can be calculated by multiplying Eq.13 by r.

$$R = 1 + K_1 * r^2 + K_2 * r^4 + K_3 * r^6 + \cdots \qquad (13)$$

- **r:** is the nominal radius of the field point.
- **R:** is the measured radius of the field point.
- **K_0 to K_7:** radial distortion coefficients.

Method:

One or several images are taken from a checkerboard pattern, as shown in Fig.33. The checkerboard is used because straight lines with localized endpoints and interior points can be detected in different orientations in the image plane (vertical, horizontal, and radial). Also, the checkerboard pattern is better in the way that if nonlinear monotonic functions are added to the intensity values of the checkerboard image (gamma correction), the corner localization will not be affected.

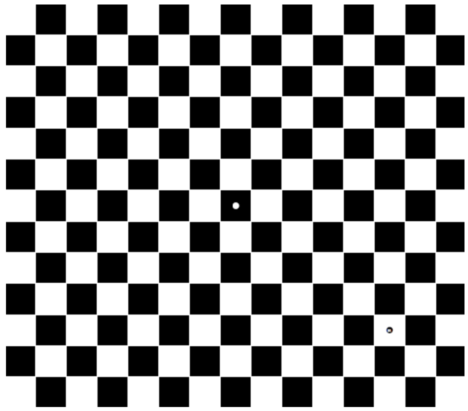


Figure 33 - Target that is used to measure distortion.

Distortion is different for different lenses. In order to be able to visualize the distortion in the image taken from the checkerboard pattern, a simple Sobel edge detection filter can be used, which turns Fig.33 into horizontal and vertical lines, as shown in Fig.34.

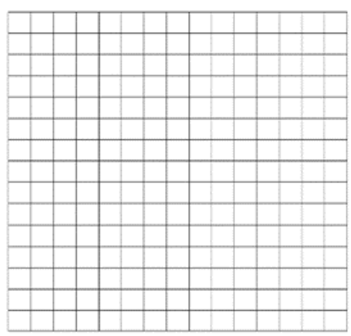


Figure 34 - MTF measurement setup

The next step is to convolve the image taken from the checkerboard pattern with a filter that detects the corners of the checkerboard pattern shown in Fig.33, which after taking the absolute value of the filter output results will be as shown in Fig.36.

-1	-1	-1	0	1	1	1
-1	-1	-1	0	1	1	1
-1	-1	-1	0	1	1	1
0	0	0	0	0	0	0
1	1	1	0	-1	-1	-1
1	1	1	0	-1	-1	-1
1	1	1	0	-1	-1	-1

Figure 35 - The convolution filter which detects the corners.

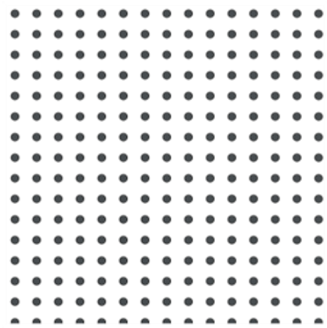


Figure 36 - Results of convolving the checkerboard image

We have vertical and horizontal distortion for each field Point. DistortionH is calculated as the distance between horizontal Actual Distance of a spot and the horizontal Predicted Distance as shown in Figure 30. DistortionV is calculated as the distance between vertical Actual Distance of a spot and the vertical Predicted Distance. The distortion is calculated by using Equation 14 and is represented in percent. The distortion coefficients must also be calculated using Equation 14 below.

$$R = r * (1 + K_1 * r^2 + K_2 * r^4) \tag{14}$$

$$(R/r - 1) = K1 * r\text{^}2 + K2 * (r\text{^}2)\text{^}2$$

- R is the measured radius of the field point.
- r is the nominal radius of the field point.

$$Y_{array} = K_1 * X_{array} + K_2 * X_{array}^2 \tag{15}$$

- $Y_{Array} = (R/r - 1)$
- $X_{Array} = r^2$
- At last, a second-order polynomial (Eq.14) is fit to the distortion values from step 6 and is forced through the origin. The fitting coefficient 1 is K_1 and coefficient 2 is K_2.

4.3 <u>**Lab MTF at Hot and Cold Temperature**</u>

Purpose: verify that product meets MTF requirements at hot and cold temperatures in the controlled test environment. Test Profiles for this experiment are shown below in Fig.37.

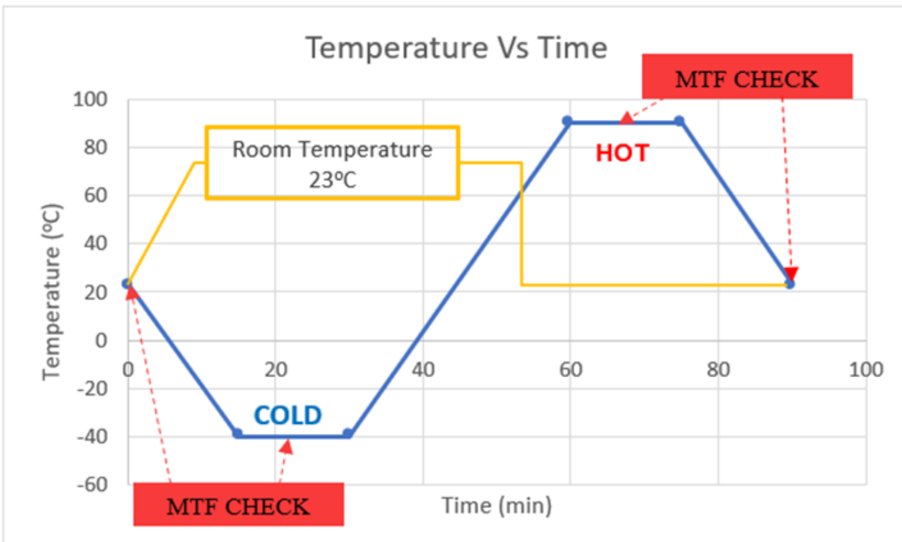


Figure 37 - Thermal cycle test sequence.

LAB MTF at room temperature:

As shown in Fig.36, the MTF is first measured at 23ºC, according to the steps mentioned in the Methodology section 4.1.

LAB MTF at hot and cold temperatures:

In the graph from Fig.36, it is shown that the hot and cold temperature in which the MTF is measured is set to be 90ºC and -40ºC respectively. The MTF is measured based on the steps discussed in the Methodology section.

4.4 Field MTF at Cold Temperature

Purpose: Verify that product meets MTF and Performance requirements at cold temperature in field test environment.

Method: The test shall be performed in two different times of day where the light conditions are either maximum amount of natural illumination or minimum amount of natural illumination (Day and Night). For day-time conditions, a clear sunny day shall be selected, with vehicle path shape shall be some form of closed loop to allow for sun to be present in four different directions with respect to the camera FOV under test. Test procedure shall be sequential per Fig.38.

Before Test: The following data shall be recorded for test condition reference at the time of test:

- Barometric Pressure;
- Humidity;
- Direct Solar Irradiance (Lux meter directed at the sun);
- Indirect solar irradiance (White screen lux meter measurement reflecting direct sunlight);
- Temperature outside vehicle;
- Spectral and lux data from secondary vehicle headlights;

Day Test:

The purpose of daytime testing is to collect camera performance data during various scenarios in terms of solar irradiance. There are two basic parts of the test. First, is the still image data collection using optical test targets, second, is the video data collection using Test Operator's facial features.

By varying sun location regarding the camera, we achieve different light condition scenarios that the camera will experience during its lifecycle.

Step 1.

During Pre-Soak the vehicle should be placed stationary with ignition-on after arriving at test location. Time of the day selected shall be between 11:00-14:00. The vehicle should be positioned with camera facing opposite direction of the sun to minimize exposure to heat. Image should be recorded, and PCB component temperature measurements should be initiated.

Step 2.

During Soak the vehicle should be stationary with ignition off, same light conditions as the Pre-Soak. Temperature should be monitored for stabilization. When temperature change is less than **+/-1 degree per 15 minutes** Soak can be considered as achieved.

Step 3.

Test operator shall enter the vehicle, turn ignition on, and record image. Video recording is then initiated, and gaze function sequence performed by the operator.

Step 4.

After Video collection is complete, the Operator shall drive the vehicle around test route, continuing video recording and temperature monitoring. Speed of the vehicle shall be between **25 and 35 mph**, and sun location shall be logged during the test to correlate temperature and performance to the sun location.

Step 5.

After a minimum of three driving loops the test is complete.

Night Test:

The purpose of night testing is to collect camera performance data during various scenarios in terms of artificial light conditions (headlight simulation). There are two basic parts of the test. First, is the still image data collection using optical test targets, second, is the video data collection using Test Operator's facial features. A secondary stationary vehicle is placed with high-beam headlights turned on. Headlight spectrum should be selected in a way where some of the irradiation spectra produced by the light passes through the camera filters – see Fig.40 for more detailed description. By varying the primary vehicle headlight location, regarding the camera, we achieve different light condition scenarios that camera will experience during its lifecycle at night time.

Step 1.

During pre-soak the vehicle should be placed stationary with ignition-on after arriving at test location. Vehicle can be positioned in any direction. Image should be recorded, and PCB component temperature measurements should be initiated.

Step 2.

During soak the vehicle should be stationary with ignition off. Temperature should be monitored for stabilization. When temperature change is less than **+/-1 degree per 15 minutes** soak can be considered as achieved.

Step 3.

Test operator shall enter the vehicle, turn ignition on, and record Image. Video recording is then initiated, and gaze function sequence performed by the operator.

Step 4.

After video collection is complete, the operator shall drive the vehicle around test route, continuing video recording and temperature monitoring. Speed of the vehicle shall be between **25 and 35 mph**.

Step 5.

After route completion the test is complete video recording shall stop.

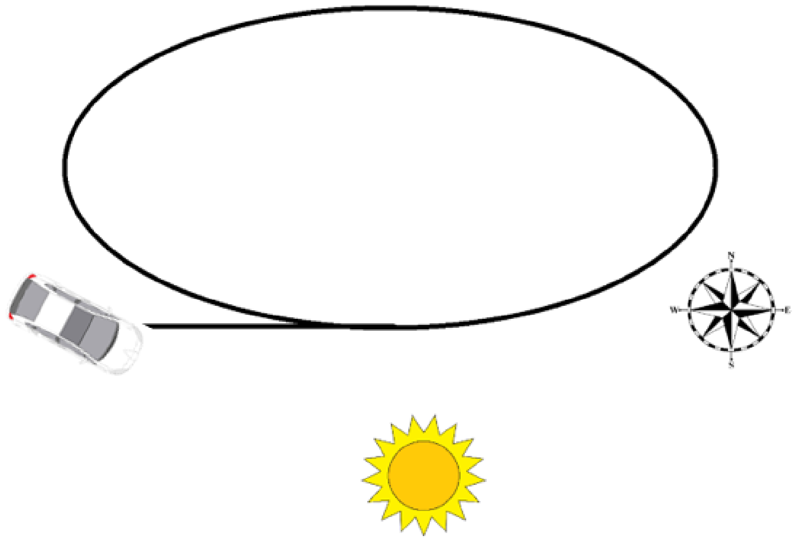


Figure 38 - Daytime Step 1,2,3 – Pre-Soak and Soak vehicle location.

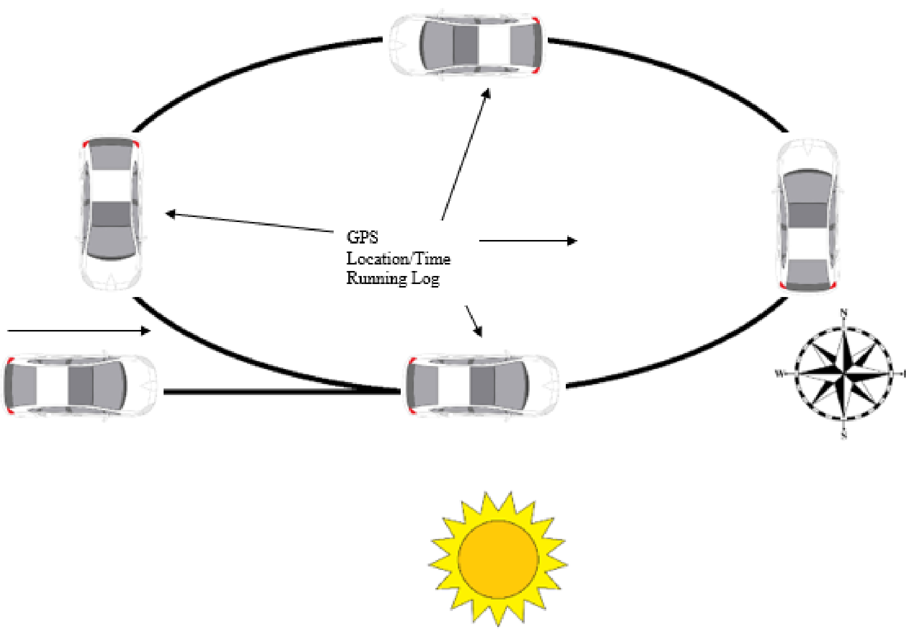


Figure 39 - Daytime Step 4,5 – Driving Test.

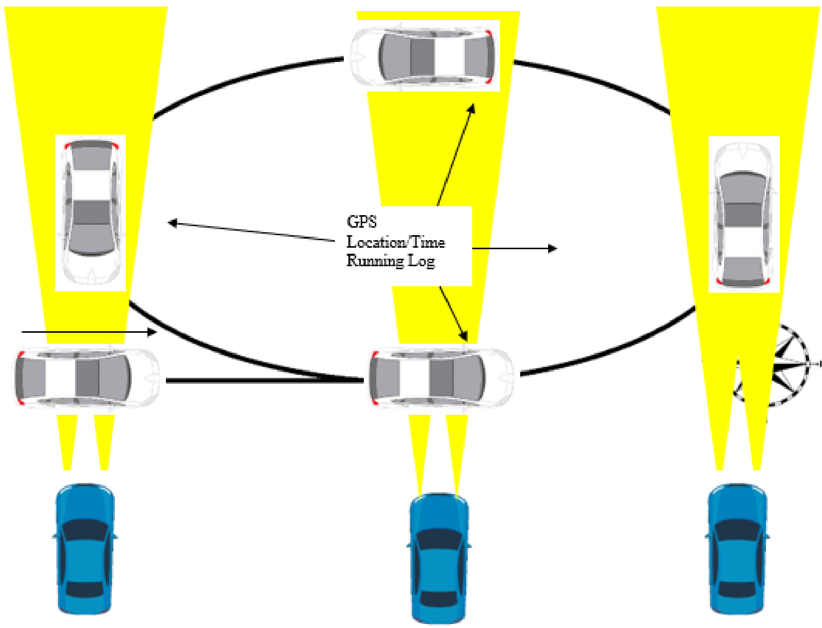


Figure 40 - Night Step 4,5 – Driving Test.

Required Equipment:

- Field MTF Target fixture
- Camera assembly with thermocouples under simulated trim cover
- Camera assembly installed in vehicle trim as intended by OEM
- Thermocouple Data Logger connected to car PC
- Car PC
- Lux Meter
- Barometer
- GPS data logger

Performance Data Analysis and Expectations

Vehicle Test Report shall follow the data collection after analysis. Vehicle Test Report shall answer the following questions about product performance, as well as include any appropriate graphs and tables serving as evidence of performance.

1. Does camera MTF meet design requirements defined in Product Application Test Specification?
2. Do all PCB components exceed operating temperature defined by component manufacturer's specification. If not, what are the limits and conditions of performance limitations?
3. Does camera algorithm perform as expected, if not, what are the limits and conditions of performance limitations?

4.5 Field MTF at Hot Temperature

Purpose: Verify that product meets MTF and Performance requirements at hot temperature in field test environment.

Method: The test shall be performed in times of day where the light conditions are maximum amount of natural illumination and at highest outside temperature. For day-time conditions a clear sunny day shall be selected, with vehicle path shape shall be some form of closed loop to allow for sun to be present in four different directions with respect to the camera FOV under test. Test procedure shall be sequential per Fig.41.

Before Test: The following data shall be recorded for test condition reference at the time of test:

- Barometric Pressure;
- Humidity;
- Direct Solar Irradiance (Lux meter directed at the sun);
- Indirect solar irradiance (White screen lux meter measurement reflecting direct sunlight);
- Temperature outside vehicle;

Test: The purpose of this test is to collect camera performance data during various scenarios in terms of solar irradiance. There are two basic parts of the test. First, is the still image data collection using optical test targets. Second, is the video data collection using Test Operator's facial features. By varying sun location regarding the camera, we achieve different light condition scenarios that camera will experience during its lifecycle.

Step 1.

During Pre-Soak the vehicle should be placed stationary with ignition-on after arriving at test location. Time of the day selected shall be between 11:00-14:00. Vehicle should be positioned with camera facing opposite direction of the sun to minimize exposure to heat. Image should be recorded, and PCB component temperature measurements should be initiated.

Step 2.

During soak the vehicle should be stationary with ignition off, same light conditions as the pre-soak. Temperature should be monitored for stabilization. When temperature change is less than **+/-1 degree per 15 minutes** soak can be considered as achieved.

Step 3.

Test operator shall enter the vehicle, turn ignition on, and record image. Video recording is then initiated, and gaze function sequence performed by the operator.

Step 4.

After video collection is complete, the operator shall drive the vehicle around test route, continuing video recording and temperature monitoring. Speed of the vehicle shall be between **25 and 35 mph**, and sun location shall be logged during the test to correlate temperature and performance to the sun location.

Step 5.

After a minimum of three driving loops the test is complete.

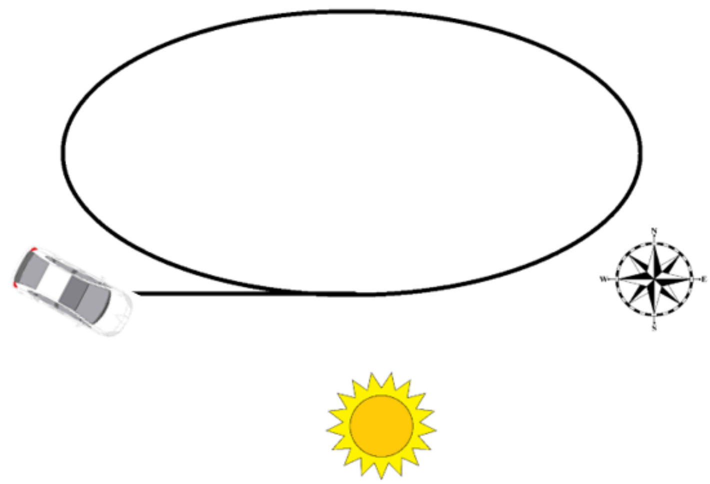


Figure 41 - Step 1,2,3 – Pre-Soak and Soak vehicle location.

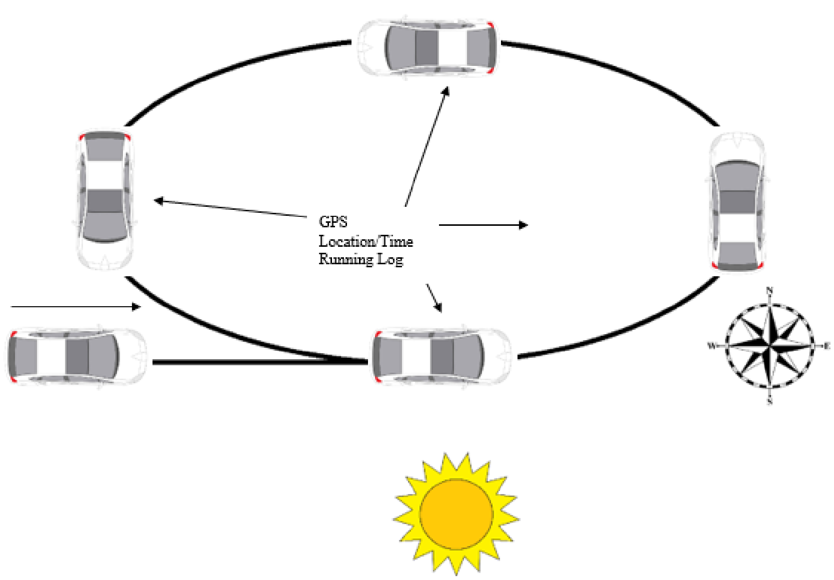


Figure 42 - Step 4,5 – Driving Test.

Required Equipment:

- Field MTF Target fixture
- Camera assembly with thermocouples under simulated trim cover
- Camera assembly installed in vehicle trim as intended by OEM
- Thermocouple data logger connected to car PC
- Car PC
- Lux Meter
- Barometer
- GPS data logger

Performance Data Analysis and Expectations

Vehicle Test Report shall follow the data collection after analysis. Vehicle Test Report shall answer the following questions about product performance, as well as include any appropriate graphs, and tables serving as evidence of performance.

- Does camera MTF meet design requirements defined in product application test specification?
- Do PCB all components exceed operating temperature defined by component manufacturer's specification. If not, what are the limits and conditions of performance limitations?
- Does camera algorithm perform as expected, if not, what are the limits and conditions of performance limitations?

4.6 **AA MTF Testing – High Temperature Degradation (HTD)**

Purpose: Verify that product meets MTF requirements after Accelerated Aging in a controlled test environment.

Method: The MTF of the system is first measured at the conditions mentioned in section 4.1, and then the system is placed in a chamber of 105^{o}C temperature and less than 10% humidity and the MTF is measured again after 1000 hours using the method mentioned in the methodology in section 4.1 as shown in Fig.43.

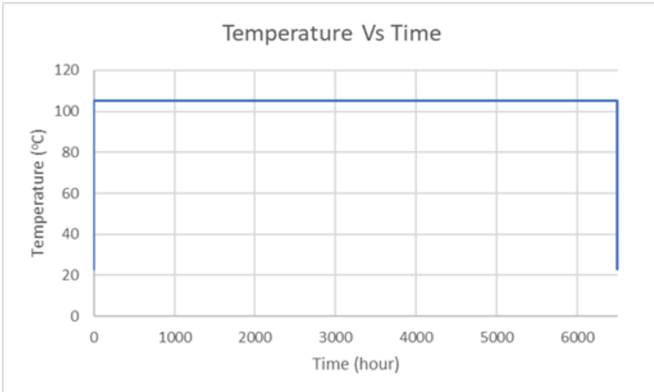


Figure 43 - Temperature vs. time for the high-temperature AA MTF testing procedure.

4.7 <u>AA MTF Testing – Humidity</u>

Purpose: Verify that product meets MTF requirements after Accelerated Aging in a controlled test environment.

Method: The MTF of the system is first measured at the conditions mentioned in section 4.1, and then the system is placed in a chamber of 85^{o}C temperature and 85% humidity and the MTF is measured again after 1000 hours using the method mentioned in the methodology in section 4.1 as shown in Fig.44.

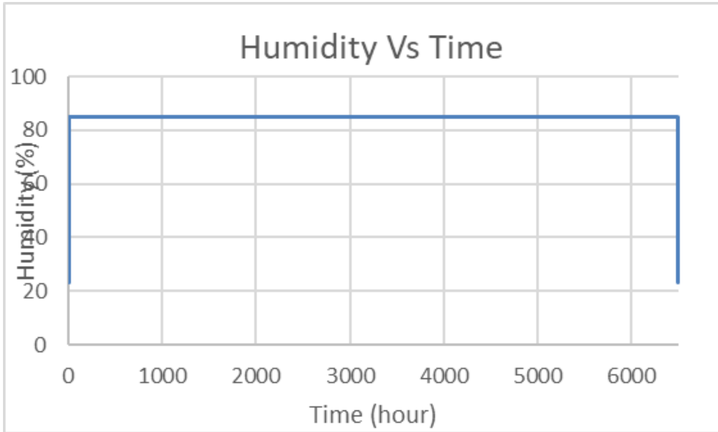


Figure 44 - Humidity vs. time for the high-temperature AA MTF testing procedure.

4.8 <u>**AA MTF Testing – Thermal Shock**</u>

Purpose: Verify that product meets MTF requirements after Accelerated Aging in a controlled test environment.

Method: The MTF of the system is first measured at the conditions mentioned in section 4.1, and then the system is placed in -40^{o}C for 20 minutes and immediately switched to 85^{o}C for 20 minutes, and this is done for 1000 cycles. After 1000 cycles are over the MTF is measured using the methodology mentioned in section 4.1 as shown in Fig.45.

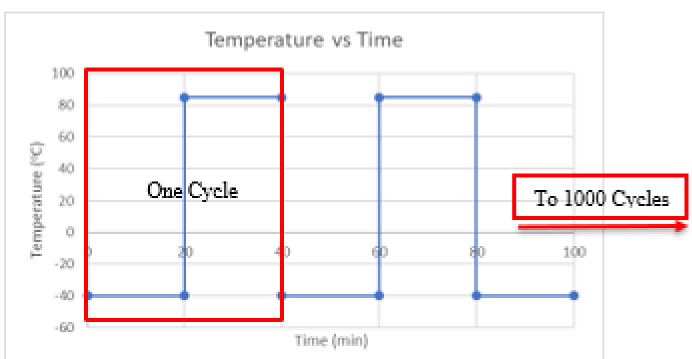


Figure 45 - Temperature vs. time for thermal shock AA MTF testing procedure.

4.9 Imager Particle Testing and Defective Pixel Testing

Purpose: Identify particles of size that is above the required limitations, and identify dead and hot pixels.

Method: An illuminating system that switches between on and off is used as shown in Fig.47.

- Natural Density (ND) filter should be placed 30.5 mm from PCB imager.
- Collimated Spotlight Assembly should be placed 25mm from ND filter.
- Exposure should be limited to 120-140 pixels.
- When the light source is on, dark pixels are identified as dead pixels and When the light source is off, light pixels are identified as live pixels.
- The dead pixels are marked dead.
- Any large group of dead pixels are identified as dust.

Also, pixels with values more than 245 and less than 10 are marked as defective as shown in Fig.46.

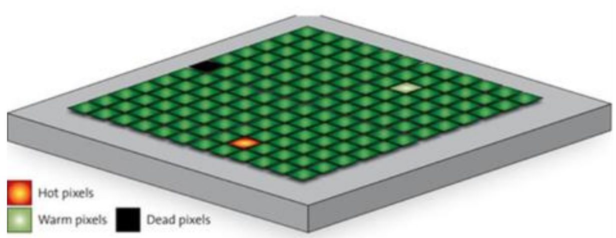


Figure 46 - How dead and hot pixels are identified.

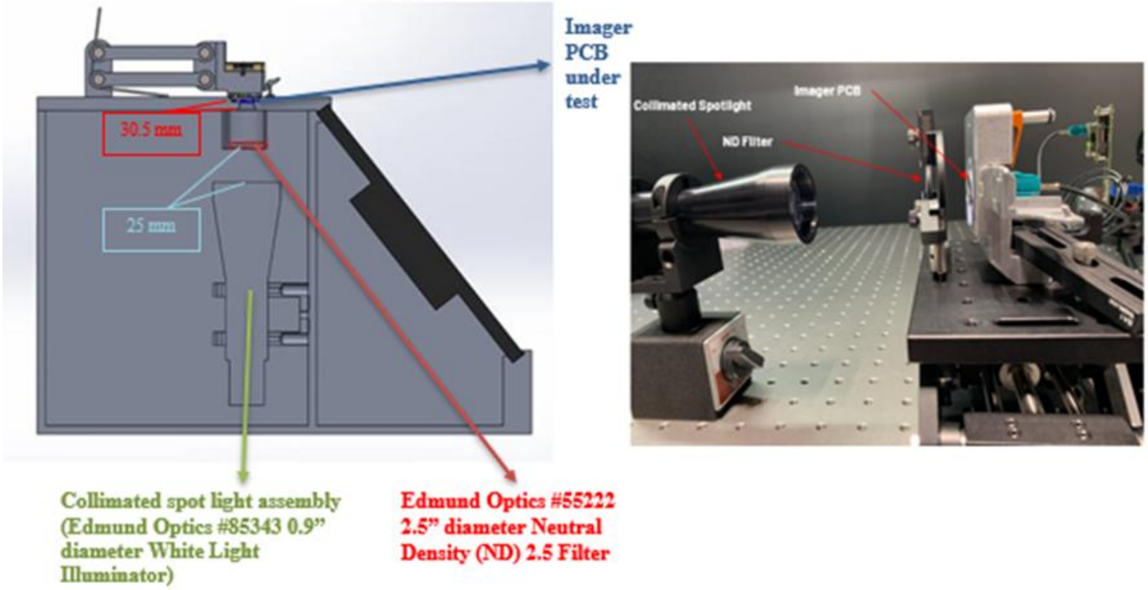


Figure 47 - Setup for identifying hot and dead pixels.

4.10 **<u>IR Light Intensity Testing</u>**

Purpose: To measure intensity of the IR LED pulses.

Method: Fig.48 shows the schematic of the setup designed to measure the intensity of IR LED pulses. To perform the procedure, two IR LED light sources are connected to a power supply, cover the eight PCB sensors as shown in Fig.48.

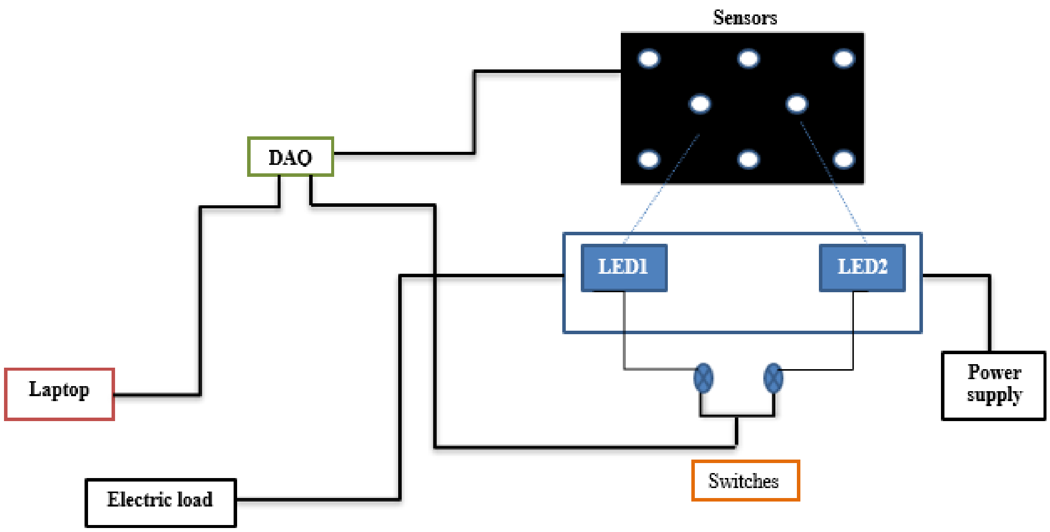


Figure 48 - Schematic of the IR Intensity testing Setup.

Each sensor includes a circuit with FDS100 Thorlabs photodiode chip. Chip responsivity is calculated is an Eq. 16 and the curve is shown in Fig.49, and is used in intensity calculation based on readout voltage from the output signal.

$$R_\lambda = \frac{I_P}{P} \tag{16}$$

- I_p is the photocurrent
- P is the light power at a given wavelength

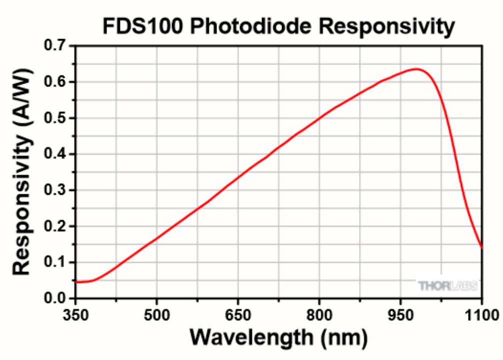


Figure 49 - Responsivity curve for FDS100 Thorlabs Photodiode.

The responsivity R_λ can be read from the plot in Fig.48 to estimate the amount of photocurrent. Which is the converted to voltage using a load resistor from the anode of the photodiode to the circuit ground through Eq.17.

$$V = R_\lambda \times P \times R_L \tag{17}$$

LED1 covers the half-right and LED2 covers the half-left sensors. The voltage is controlled by the laptop through the DAQ device. The DAQ is connected to two switches that pulse the LEDs at a rate given by the laptop through the DAQ which the rate is shown in Fig.50 In order to avoid voltage-drop caused by the increase in the LEDs temperature (due to the pulsing procedure), an electric load is supplied which makes sure the LED voltage stays stable. The output power (P) is then read through the laptop. Then the Intensity can be calculated using the current table Tab.11, provided by the LED manufacturer.

Table 11 - Current versus pulse time (provided by the manufacturer).

Current Amplitude (A)	On Time (micro seconds)	Off Time (micro seconds)
1.0	4000	41000
1.5	2000	43000
2.0	500	44500
2.5	500	44500
3.0	300	44700
3.5	200	44800
4.0	150	44850
4.5	100	44900
5.0	50	44950
	Sensor Delay	10
	Sensor On-Time	25

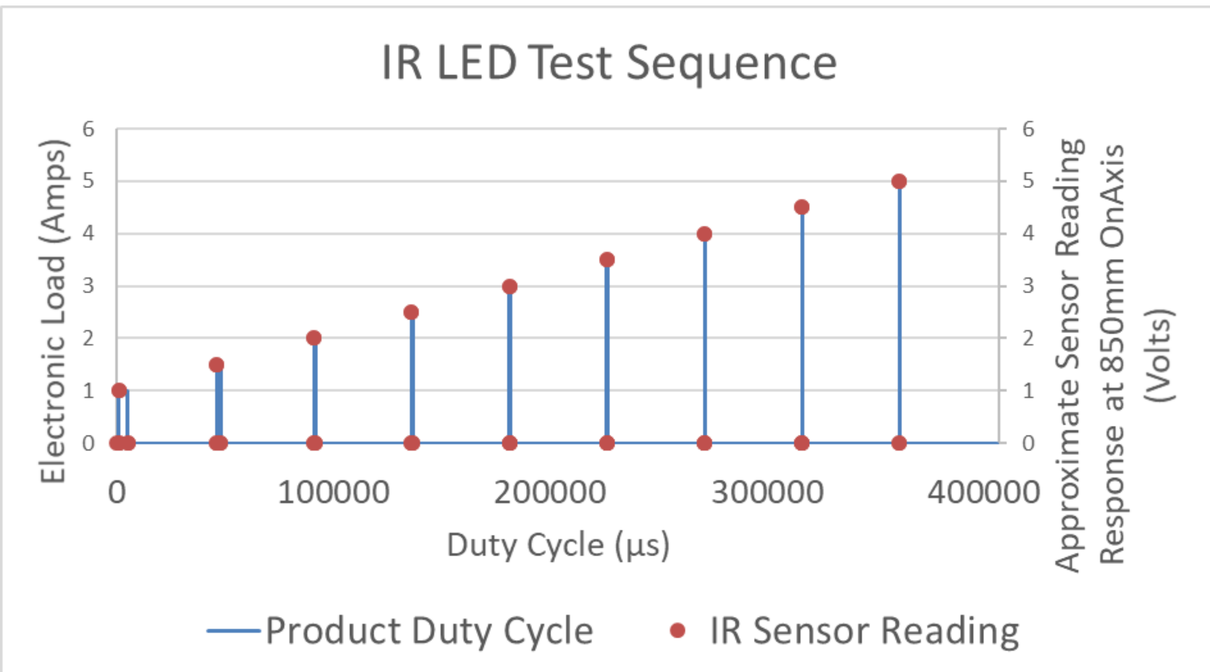


Figure 50 - IR LED test sequence.

Using the data from Tab.11 and inserting the current value into Eq.18 below, the intensity is calculated.

$$I = \frac{P}{A} = \frac{P}{\pi(d/2)^2} \quad (18)$$

- A is the area of the photosensor
- D is the diameter of the photosensor provided by the manufacturer

4.11 **Stray Light Testing**

Purpose: Measure stray light in the system quantified as veiling glare. Images that are created by digital cameras capture lighter than the scene light. Stray light (flare) can cause a reduction in the contrast of the image.

Method: Image processing algorithms can help with flare but not always because of the variable nature of the flare. Because of this, it is important that the flare light which remains in the processed images is measured. Lenses, camera bodies, image sensors and image processing can all be causing flare, so it is important to quantify the performance of the camera system. In order to measure Image flare, a setup as shown in Fig. 51 was used, which includes a 2800K Tungsten Blackbody Source with optical fiber and the camera. The diameter of the outcoming light from the optical fiber is 400 µm. A reference picture must be captured of a ruler to help us understand the magnification of the camera at 100 mm. The magnification must be included as a scaling factor.

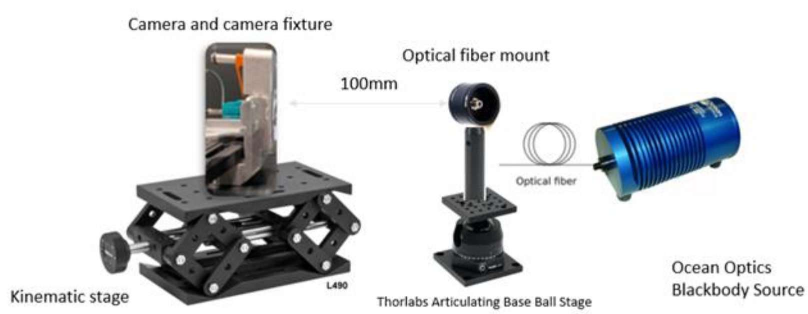


Figure 51 - Schematic of the setup used for measuring Image flare.

Algorithm for measuring Flare:

- Take picture of a circular backlit scale
- Find the ratio below
- C= $\frac{area\ of\ the\ image\ of\ the\ scale\ (in\ pixel\ counts)}{area\ of\ the\ actual\ scale\ (in\ mm)}$
- N=$Size\ of\ the\ beam\ without\ flare\ (pixel\ counts) = size\ of\ the\ beam\ in\ (mm) *$ C
- M=the number of saturated pixels (pixel value 255)
- T=total number of pixels (1280*960)
- Flare index=(M-N)/(T)

Algorithm for measuring Ghost Image:

- Take picture of a circular backlit scale
- Find the ratio below
- C= $\frac{area\ of\ the\ image\ of\ the\ scale\ (in\ pixel\ counts)}{area\ of\ the\ actual\ scale\ (in\ mm)}$
- N=$Size\ of\ the\ beam\ without\ flare\ (pixel\ counts) = size\ of\ the\ beam\ in\ (mm) *$ C
- M=the number of saturated pixels (pixel value 255)
- X= the number of unsaturated pixels in any of 7 different bins: (1-32), (33-64), (65-96), (97-128), (129-160), (161-192), (193-224), (225-254)
- T=total number of pixels (1280*960)
- Ghost effect=(X)/(T)

4.12 <u>Saturation Testing</u>

Purpose: Test image for saturated pixels to prevent incorrect lighting conditions resulting in MTF error.

Method: Perform Histogram analysis of the entire image, if 1% of pix values exceeds 254 bitmap value, consider the image to be saturated. The results of saturation testing for a saturated, normal and undersaturated image are shown in Fig. 52, 53, and 54, respectively.

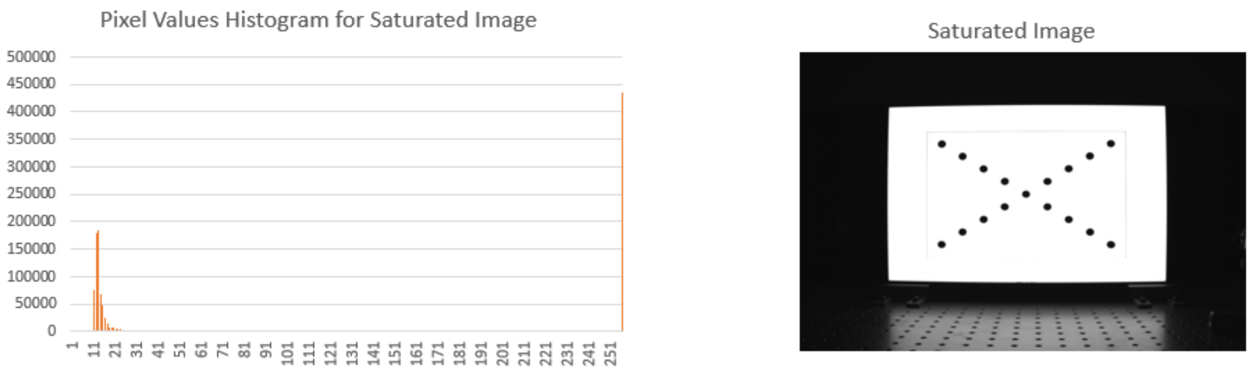


Figure 52 - Results for Saturation testing of a saturated image.

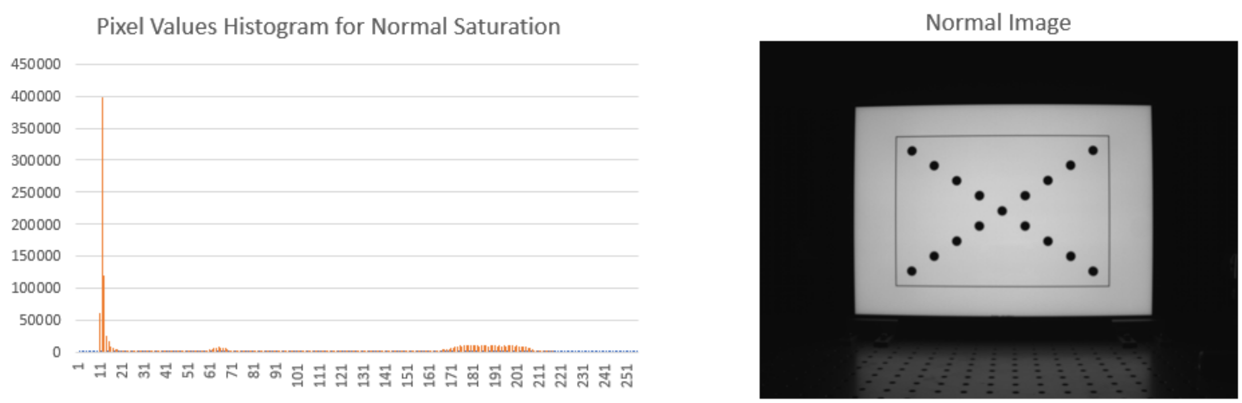


Figure 53 - Results for Saturation testing of a normal image.

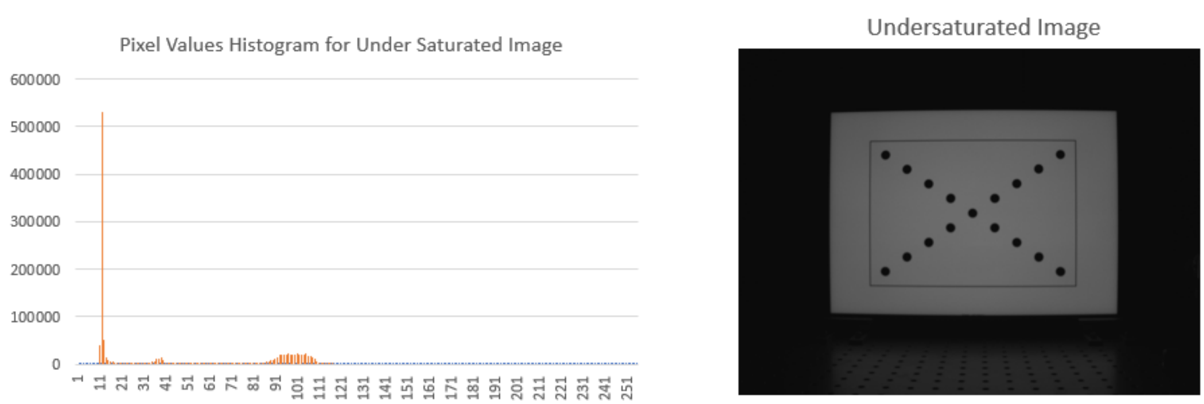


Figure 54 - Results for Saturation testing of an undersaturated image.

4.13 **EFL Testing**

Purpose: Calculate camera Horizontal and Vertical Effective Focal Length

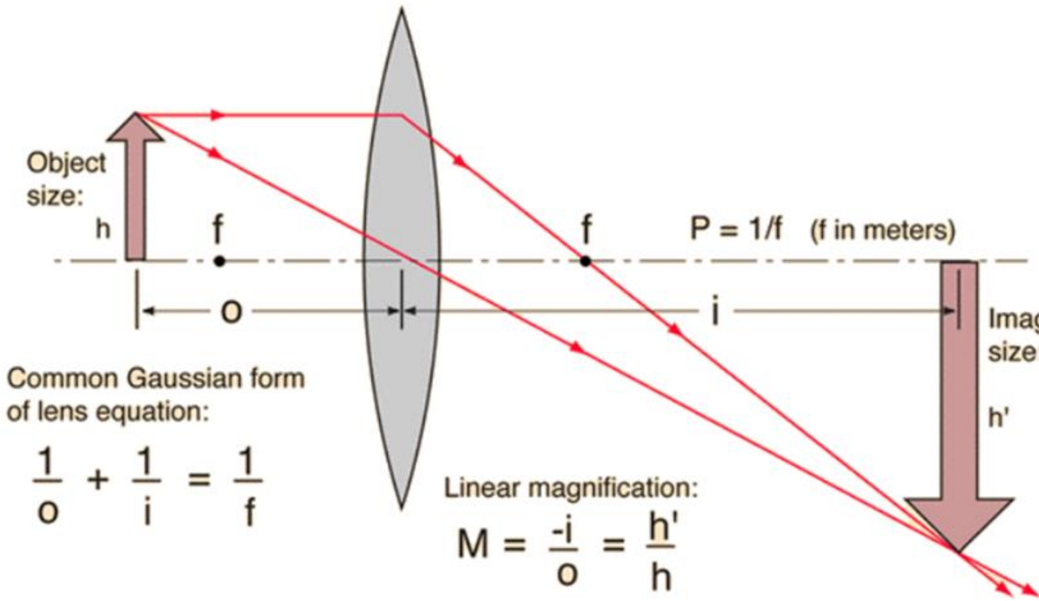


Figure 55 - Thin Lens Equation Parameter Definitions.

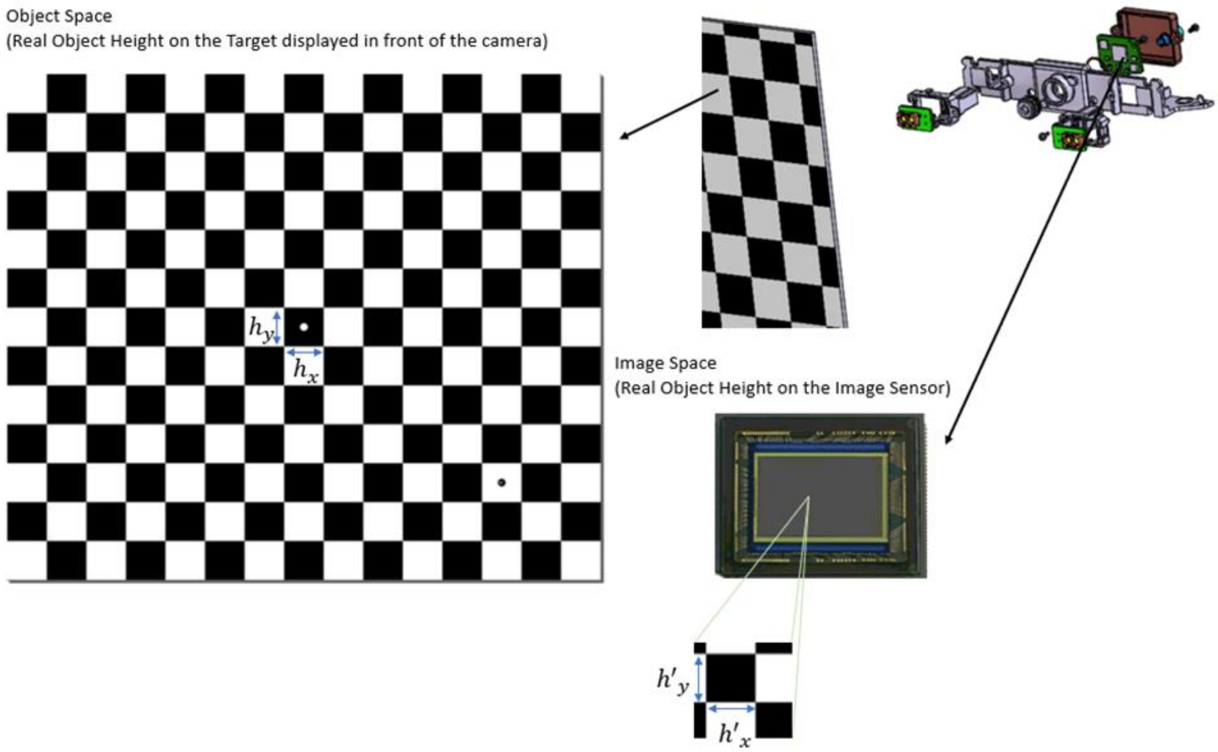


Figure 56 - Optical Space Definitions.

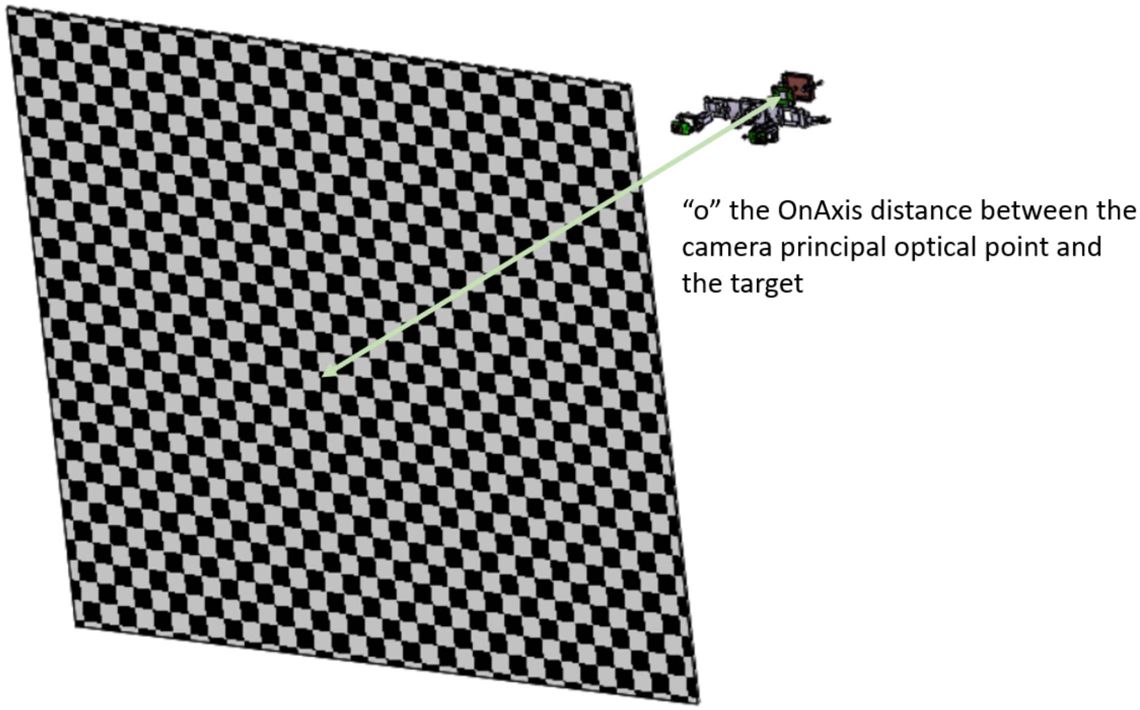


Figure 57 - Optical Path Definitions.

$f_x = EFL(Horizontal)$

$f_y = EFL(Vertical)$

$$f_x = \frac{-o*h'_x}{h_x-h'_x} \quad (19)$$

$$f_y = \frac{-o*h'_y}{h_y-h'_y}$$

Constants (Examples):

o – is the target distance. For the DMS product the optimal target distance is currently set at 850mm from the front surface of the lens; The principal point is located ~1mm into the lens from the front surface, and therefore the total distance is ~851mm.

h_x – is the actual printed horizontal box size (53.333mm)

h_y – is the actual printed horizontal box size (53.846mm)

h'_x – is the size of horizontal box width in pixels from the image, times the pixel pitch (40pix*3.75*10^-3mm)

h'_y – is the size of vertical box height in pixels from the image, times the pixel pitch (41pix*3.75*10^-3mm)

4.14 <u>**Centration/Rotation Testing**</u>

Purpose: Verifying the centration and rotation of the test target and making sure it is not above the limits.

Method: To make sure the system is calibrated as shown in Fig.58, the edges surrounding the test charts shall be green, if it is red, it is not calibrated. The horizontal and vertical distance between the central test chart and the center of the test target (black background) is measured which gives us two numbers the vertical and the horizontal centration.

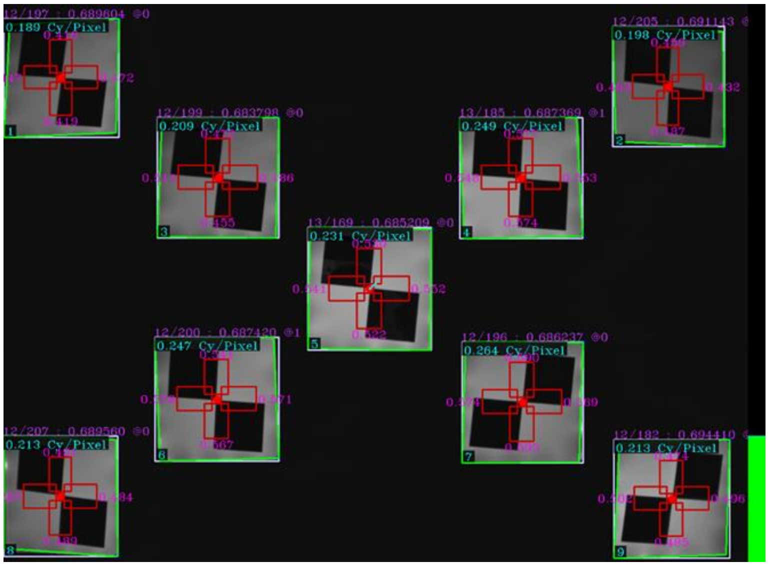


Figure 58 - MTF Calibration

For measuring rotation, the central test chart is eliminated and the rotation angle of each of the test charts is measured related to the horizontal axis. Then the average of these rotating angles is calculated and is shown as the rotation of the system. The rotation shall not be more than 5^o and less than -5^o.

4.15 **Camera Signal-To-Noise-Ratio (SNR) Test**

Purpose: Measuring the SNR and verifying it is as required.

The SNR evaluates the data found in an image. It is basically an explanation of how accurately the signal's quality in the object is replicated in the image using the machine vision algorithm.

The definition is shown in Eq.21 below

$$\boldsymbol{Q_{total}} = \frac{\boldsymbol{g_{SNR} L_{SNR}}}{\boldsymbol{\sigma_{total}}} \tag{20}$$

- g_{SNR} is the incremental gain which is the first derivative of the OECF curve
- L_{SNR} is the luminance at which the total, fixed pattern and temporal signal-to-noise ratios are measured, which is $0.13 \times L_{ref}$.
- L_{ref} is the inverse log of the log luminance value at the reference luminance, R_{ref}. given by Eq. 22

  $$R_{ref} = S^{-1}(I)|_{I=245} \tag{21}$$

  - S^{-1} is the inverse of the OECF curve
  - I is the pixel value

4.16 **Camera Dynamic Range Test**

Purpose: Measuring the Dynamic range and verifying it is as required.

Dynamic range quantifies the working range of a camera in which usable data can be extracted. In other words, it illustrates the brightest and darkest areas of a scene that can be captured in a single image and still be read. The dynamic range of a digital still camera is the ratio of the maximum unclipped input luminance level (L_{sat}) to the minimum input luminance level (L_{min}), with a signal-to-temporal noise-ratio of at least 1. The dynamic range, DR, is given by Eq.22.

$$D_r = \frac{L_{sat}}{L_{min}} \tag{22}$$

The difference between SNR and DR is shown in Fig.59.

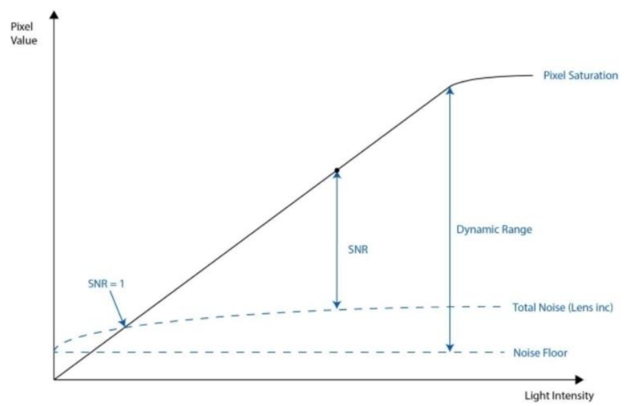


Figure 59 - SNR and DR visualization.

5 Chapter 5 – Final Design, Results and Analysis

5.1 Final Design

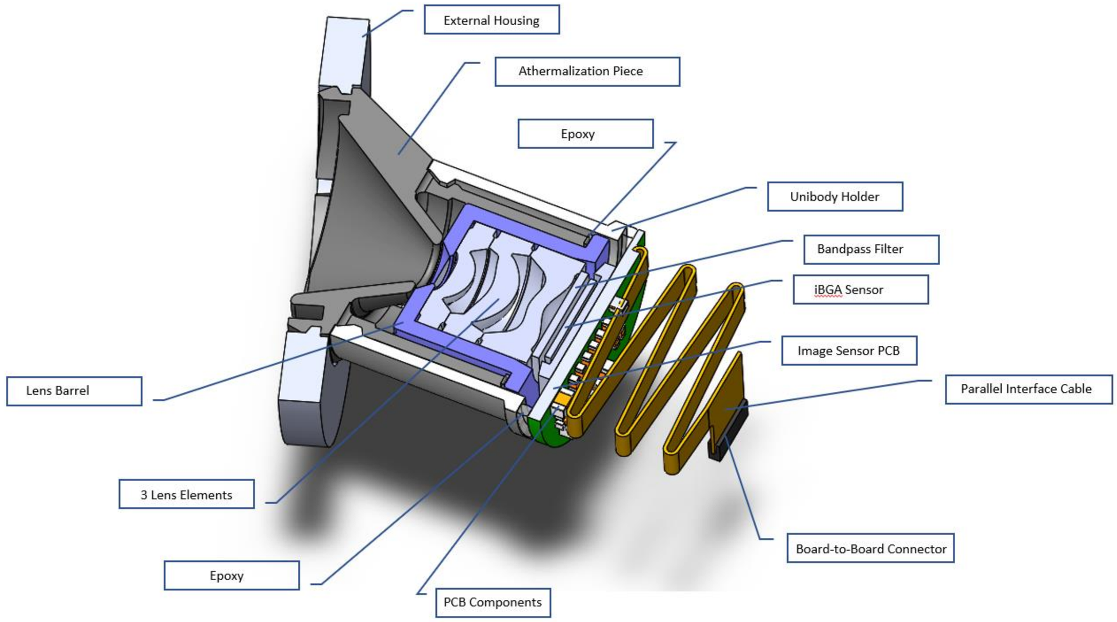


Figure 60 - Distortion target that is used to measure distortion.

In the final design, the camera assembly consists of external housing (not shown), main board with processor and all support electronics (not shown), and the imager assembly. The imager assembly shown in Fig.60 consists of Unibody assembly and Imager PCB. The unibody assembly contains an athermalization piece that has an attached lens barrel assembly, as well as a Unibody holder that snaps into the athermalization piece. As shown in Fig.60, and Fig.61, imager assembly is then 5 or 6-axis aligned onto an imager PCB for camera focus tested in different regions of interest. Once aligned, the epoxy is UV cured, then placed into an oven for thermal curing. After thermal cure the assembly is tested again for focus verification and assembled into the main housing of the final product.

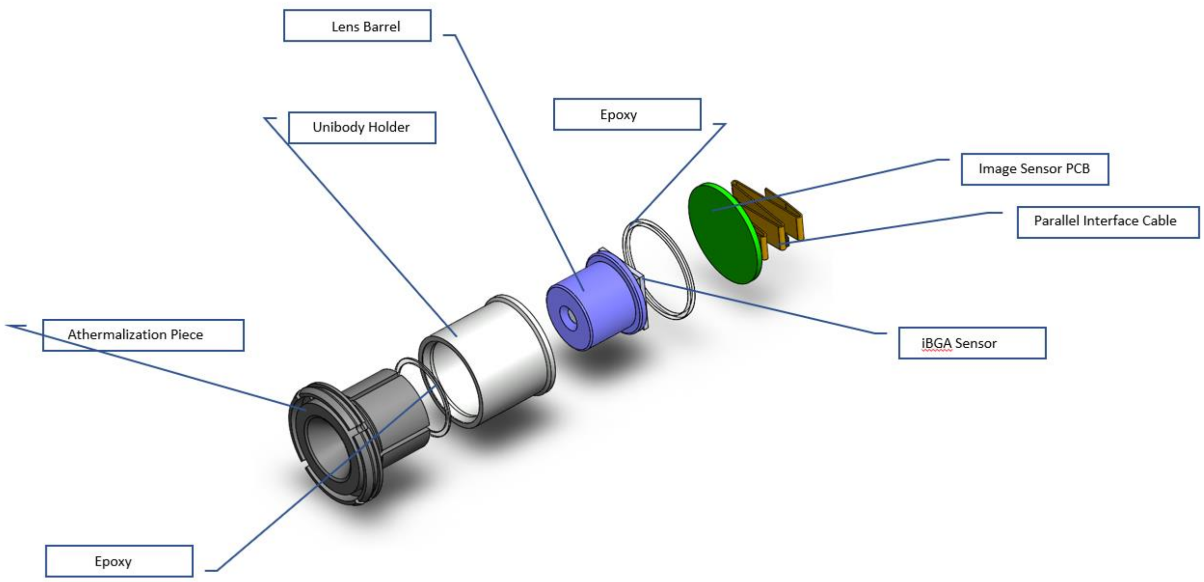


Figure 61 - Exploded View of the Final Camera Assembly Prototype

The unibody of the lens assembly typically comes from the lens assembly supplier. The lens supplier is responsible for molding the lens elements, sourcing die-casted lens barrel piece, then assembling 3 lens elements into the barrel in correct order, then attaching a bypass filter element via thermal epoxy. After barrel assembly is complete, the lens supplier then assembles the unibody of the lens. As shown in Fig.61, the first step of the unibody assembly is bonding of the athermalization piece to the lens barrel assembly. The next step is Unibody holder is then snapped into the athermalization piece, after this the lens supplier operation is complete, and product is shipped to a camera assembly plant.

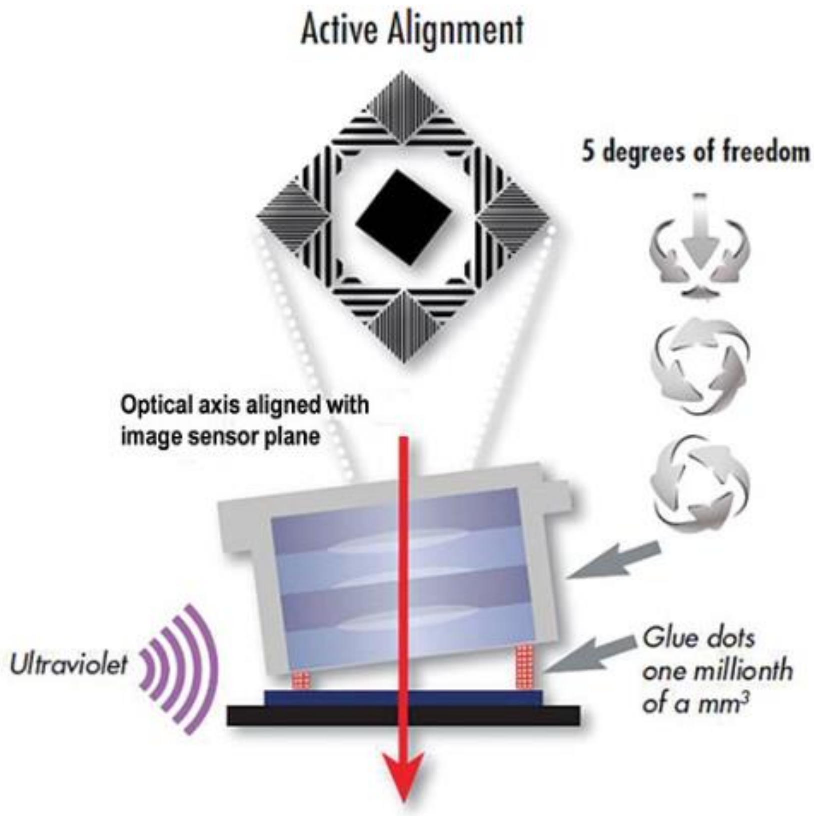


Figure 62 - Example of Active Alignment of a lens onto an image sensor PCB [49].

During active alignment, PCB assemblies (Fig.62) are loaded into special holders, accompanied by unibody lens assemblies. Image sensor PCBs are first inspected for pixel defects (described in 4.1.9), then typically cleaned with either CO2 cleaning process, or plasma treatment, to remove router dust and particles (from PCB routing process). Next, the epoxy is dispensed either onto the lens or PCB mating surface, and active aligned to achieve desired focus specification as shown in Fig.62 and Fig.63.

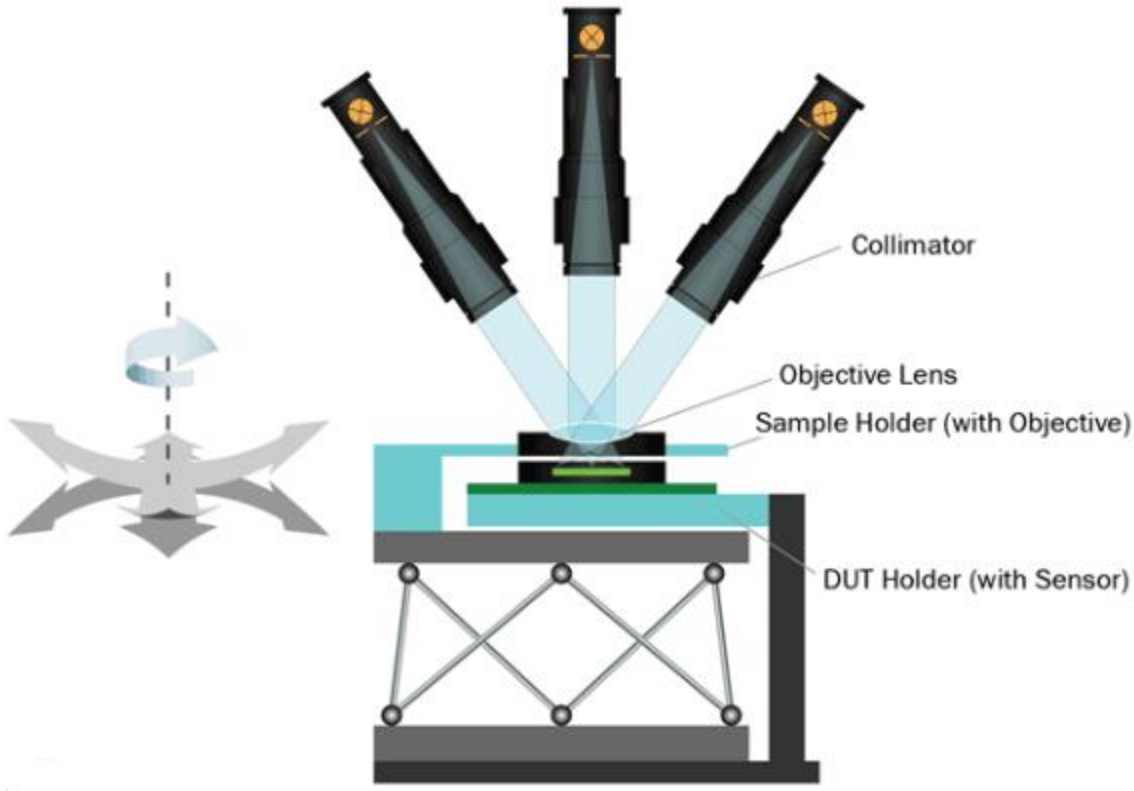


Figure 63 - Example of an optical setup required for active alignment [30].

The optical setup required for active alignment typically depends on the application. However, most of the time setup contains motorized collimated target projectors to simulate object plane without requiring actual focus distance footprint. For example, if the camera needs to be focused at 10 meters, instead of placing objects used for focus (described in 4.1.1) at an actual distance of 10 meters, collimated target projectors are used to “fool” camera into thinking that target that is located a tenth of centimeters away, is at 10 meters. The mechanism behind collimated projection optics is not covered in this paper, as this is an entirely separate topic that deserves its own dissertation.

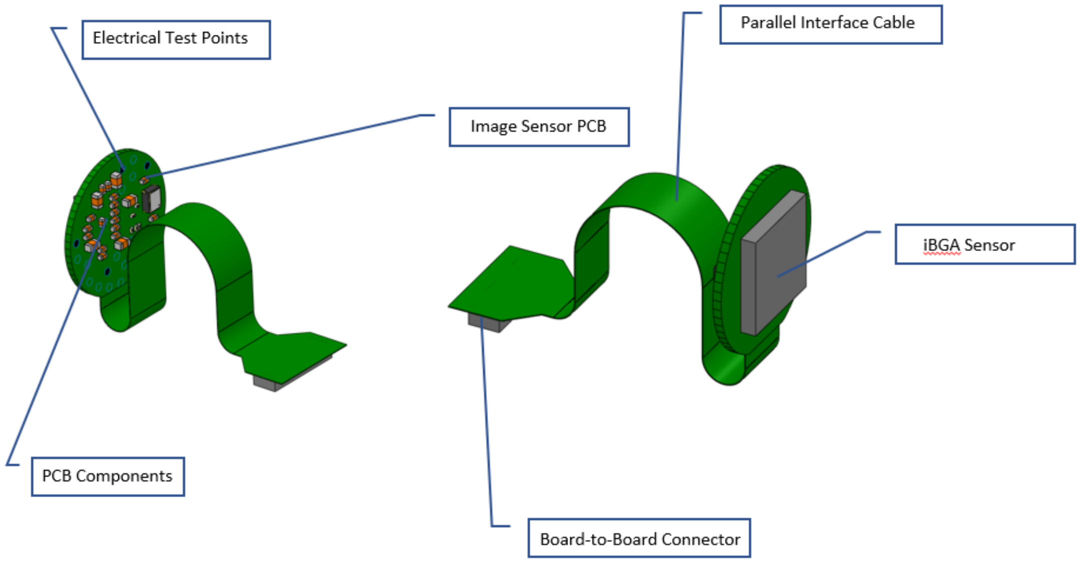


Figure 64 - Example of an imager assembly PCB prototype

In order to achieve optical focus desired, the iBGA image sensor (shown in Fig.64) mechanical plane needs to be located perfectly perpendicular to an optical axis of the lens. In order to achieve this, rays of light falling onto the image sensor surface need to intersect each other in different parts of the imager surface. In lens design, this phenomenon is typically described by MTF requirements for various "Fields of View." For example, MTF requirements are typically higher in the center of an image and could be the lowest in 80 percent of the concentric image circle of the field of view (described in 4.1.1). Shown in Fig.65, is the final design ray trace diagram that displays how light rays collected by the product lens are landing onto the image plane when the camera is perfectly aligned to the image sensor. Of course, there are multiple factors that affect this alignment, and there is a distribution of quality of the focus that is described in the Analysis section of this paper.

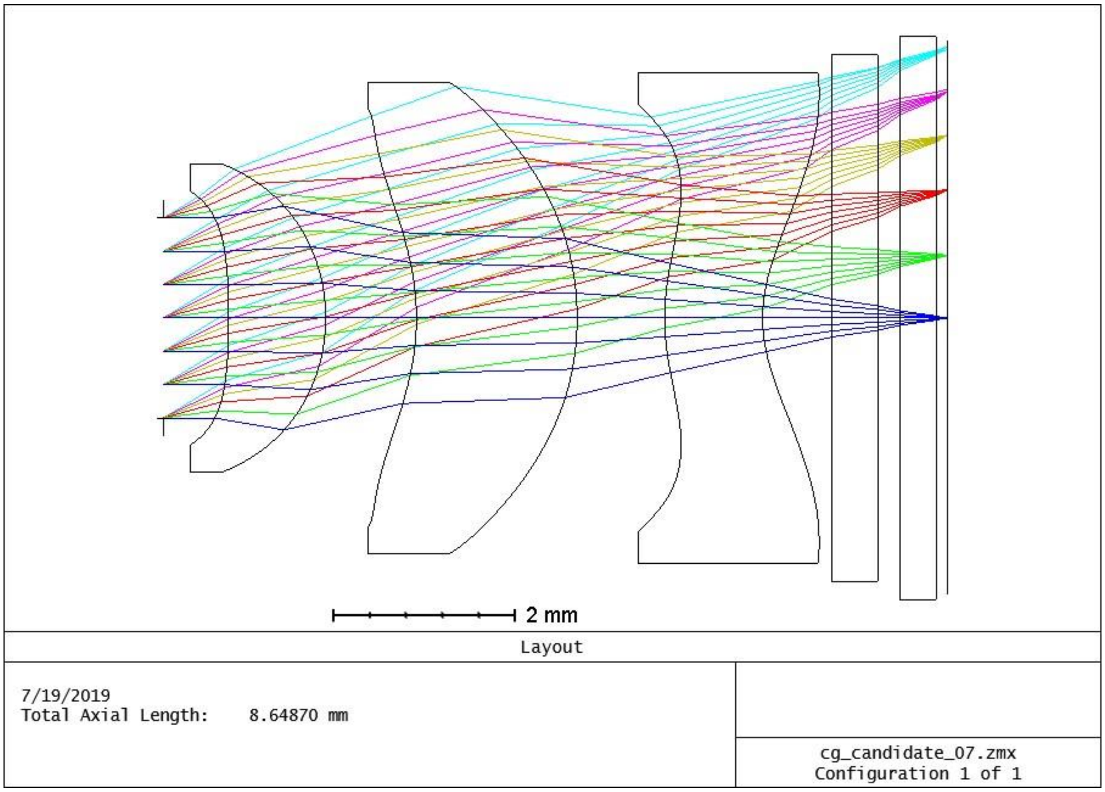


Figure 65 - Prototype lens simulation in the best focus position for this final Zemax design.

5.2 **Analysis**

The first part of design analysis is the Polychromatic Diffraction MTF shown in Fig.66. In this analysis, the design shows theoretical performance of the lens assembly across a full range of the spatial frequencies, with the maximum being at Nyquist frequency of the sensor. Since the design goal was to achieve 50% MTF On-Axis, 40% in 40% FOV, and 20% in the 80%FOV, this design accomplishes this goal and accommodates for 20% MTF buffer required for MTF loss due to imager variation, manufacturing, and lens element tolerances.

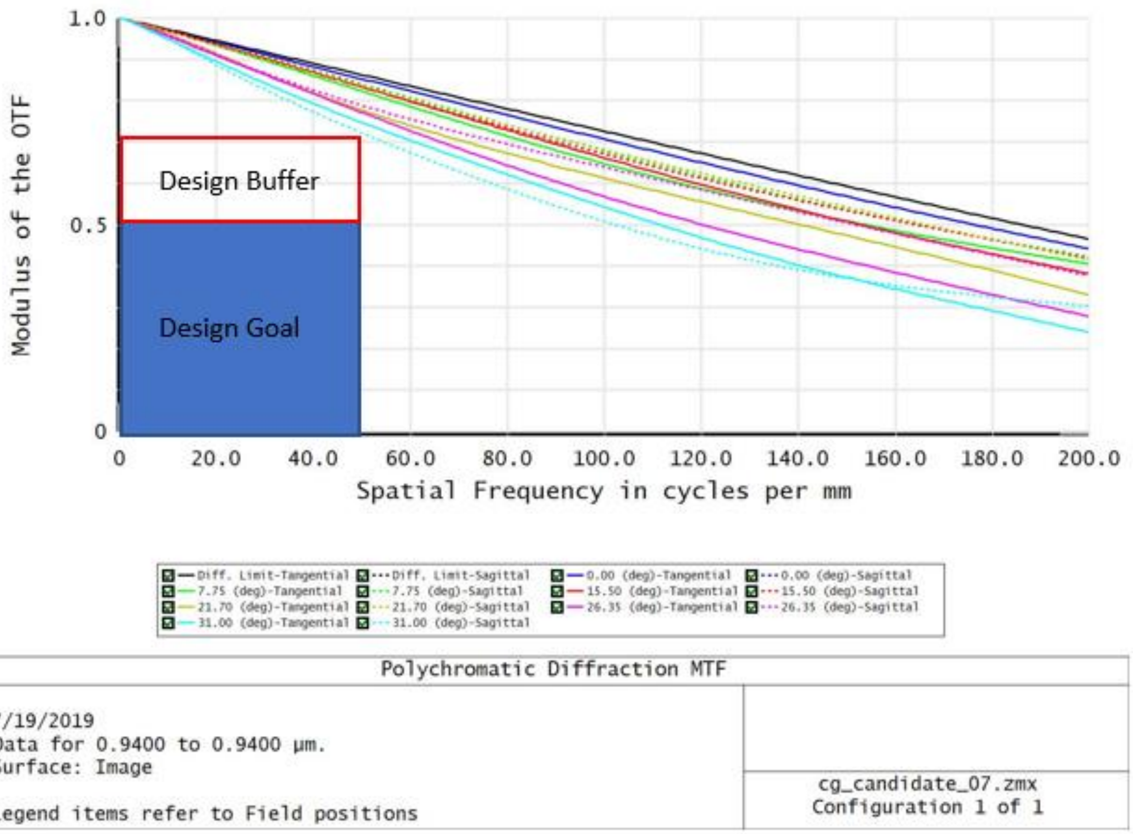


Figure 66 - Spatial Frequency response of the system.

The second part of the design performance analysis is the Depth of Focus Evaluation. Shown in Fig.67 the MTF graph shows ideal system performance for all Fields of View with the modeled design goal, and design buffer. DOF for this design is 40 microns in buffer zone, and approximately 20 microns in the Design Goal zone. The expected variation if the final product will result in lenses to range from 5 to 40 microns in DOF at 50lppmm, which is enough for a lean manufacturing process. If manufactured within target Cpk of 1.67 (6 standard deviations) per Green Belt lean manufacturing requirements, this design will yield 99.9% first pass during camera assembly process.

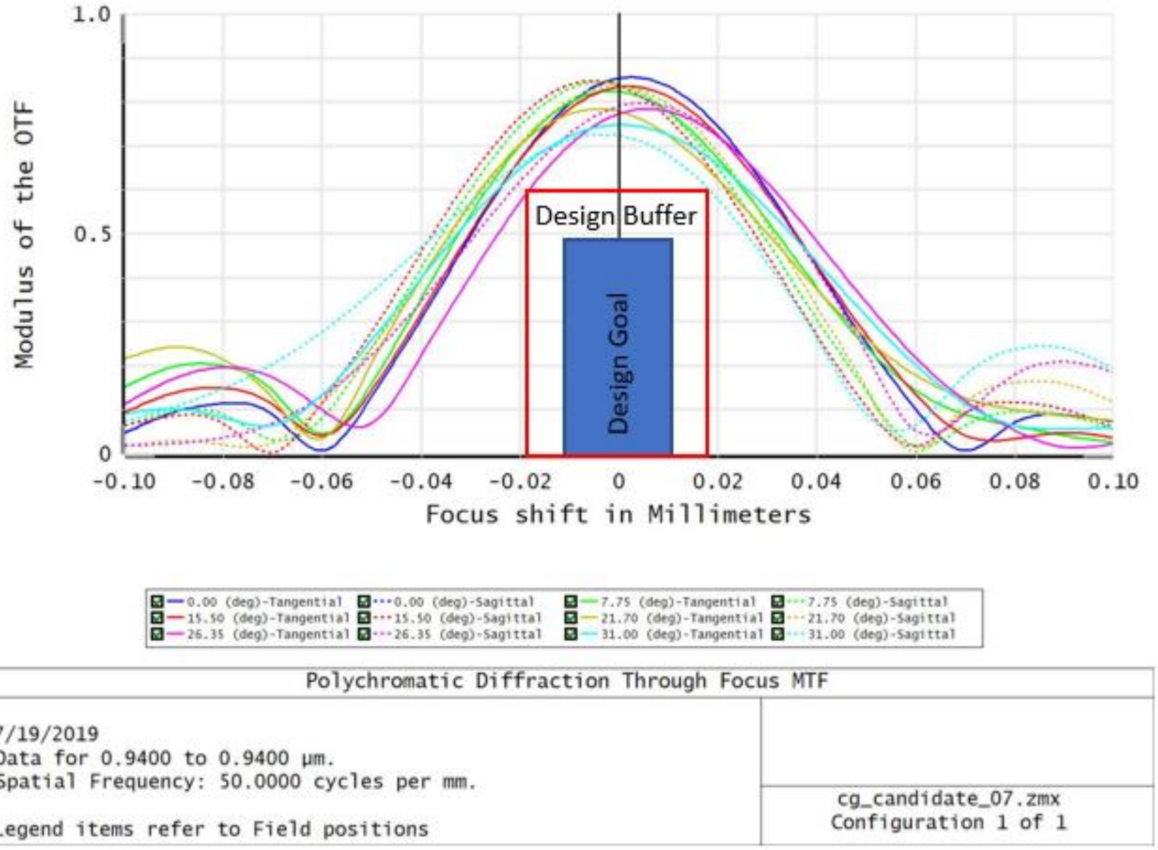


Figure 67 - Through focus simulation showing Depth of Focus design goal and buffer.

The third part of the design evaluation is the theoretical performance of relative illumination of the image sensor by the light focused with the lens. The design goal is 60% or higher illumination at half field, and buffer for the design is expected 20% more. Shown in Fig.68, analysis shows that both design and buffer are achieving target performance.

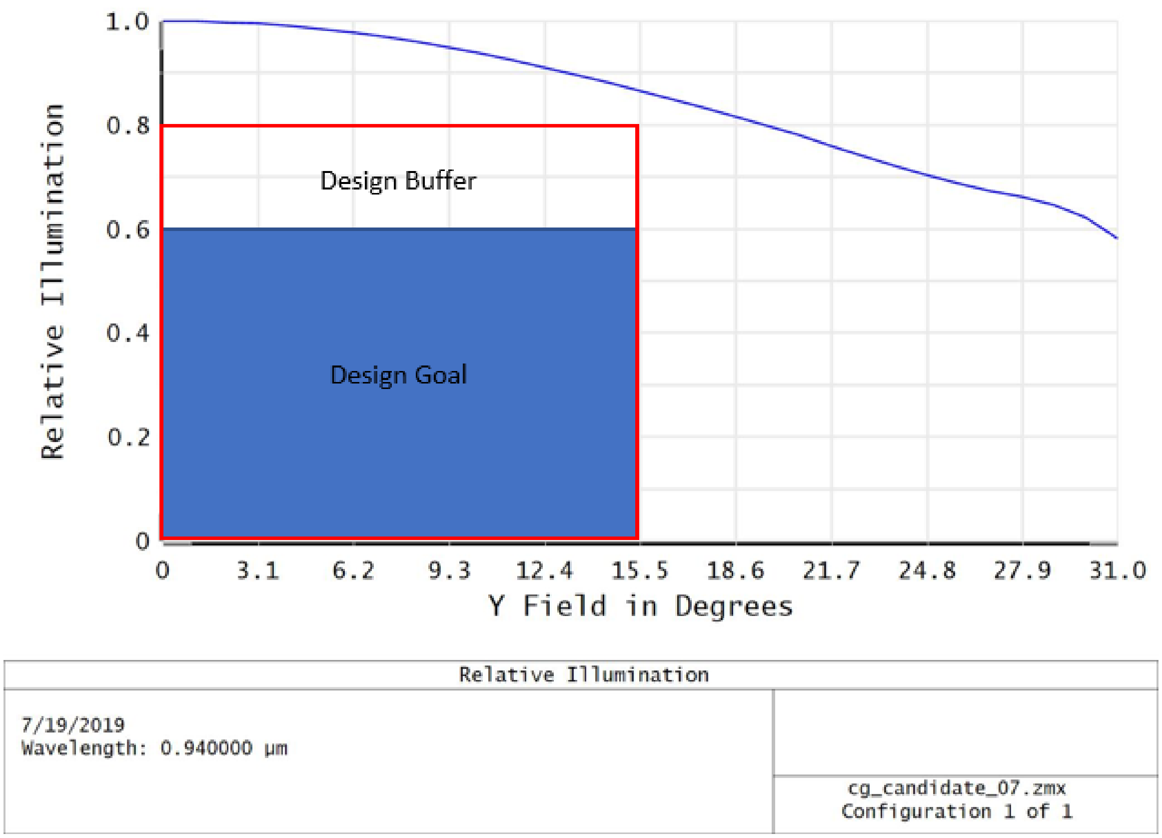


Figure 68 - Relative Illumination simulation showing design goal and buffer.

The fourth part of the design evaluation is understanding the thermal shift of the design, in order to calculate the correct size of the athermalization piece. The thermal shift analysis shows thermal expansion of +/-80 microns for design requirement temperature of -40C to +85C shown in Fig.69. There is no design goal for this analysis, as this simply drives the design for the athermalization spacer.

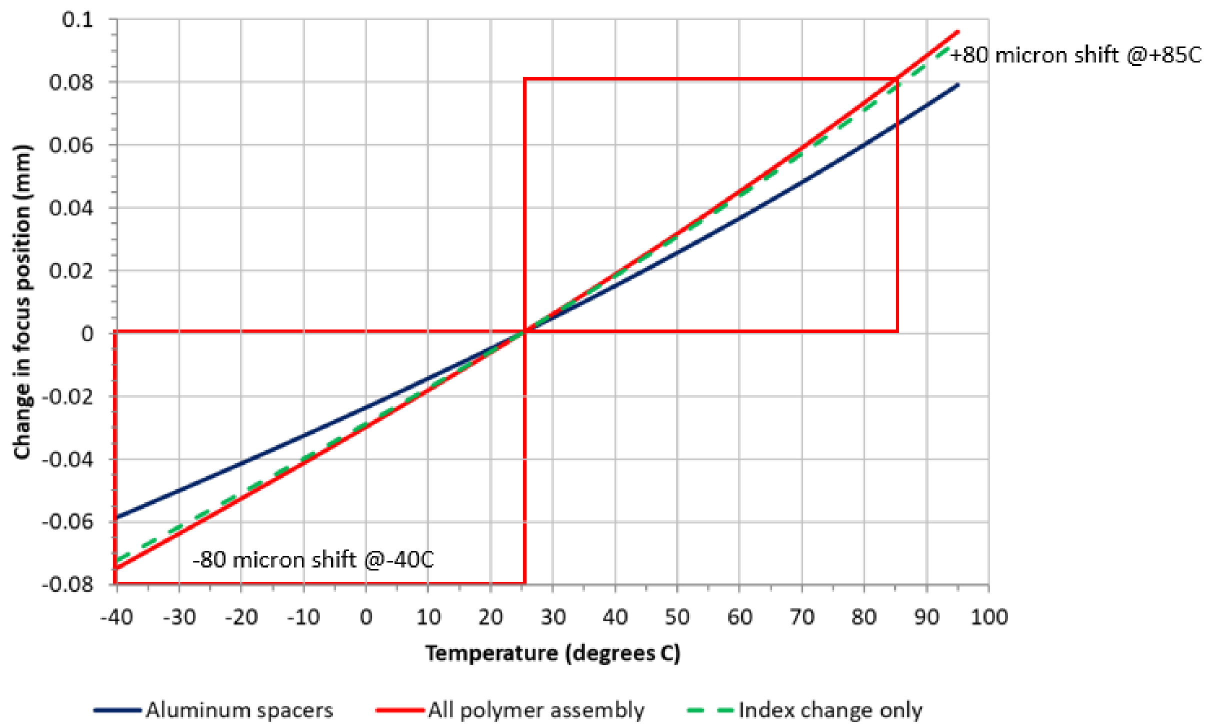
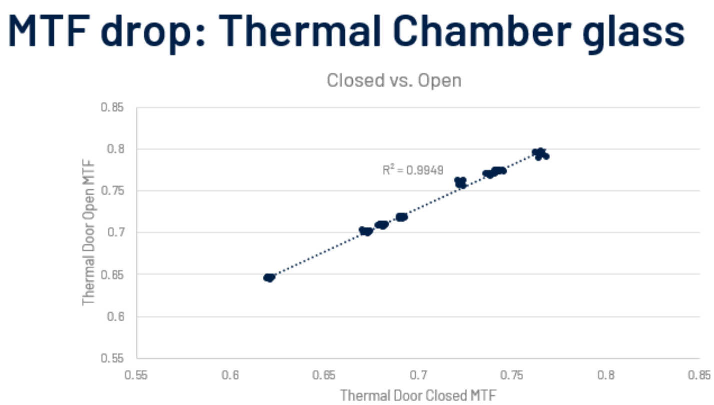


Figure 69 - Prototype lens design Thermal Shift Performance.

The fifth part of the design evaluation is the actual testing analysis of the thermal performance of the camera assembly. Initially, the camera is placed into a thermal chamber and mounted looking through chamber port outside, where an array of MTF targets is aligned with the camera assembly. Thermal cycle testing is then performed (see section 4.1.3 for details), and results are analyzed. Shown in Fig.70, is the compensation analysis for the MTF loss due to refraction occurring in 6 pane chamber glass that the camera looks through. In order to accurately evaluate MTF values, a compensation study is performed, and offset values are generated to be added to the MTF results during Cold and Hot cycles of the test. Future improvements of this test could also include an optical oven testing with better glass port design, dry purge, and offset values that will reflect the fact that MTF loss due to refraction is also different at Cold and Hot temperatures. However, for the sake of simplicity, it is enough to understand overall design performance by disregarding a small error by implementing design buffer limits. Results show that an average factor of 3% MTF needs to be added to the MTF values collected through the glass during Hot and Cold cycles.



ROI	Average MTF Door Closed	Average MTF Door Open	Difference
MA01	0.766	0.794	0.029
MA02	0.743	0.774	0.031
MA03	0.723	0.759	0.037
MA04	0.739	0.770	0.031
MA05	0.742	0.773	0.031
MA06	0.621	0.646	0.025
MA07	0.692	0.718	0.026
MA08	0.681	0.709	0.028
MA09	0.673	0.701	0.029
		Average:	0.030

Figure 70 - Average MTF loss offset analysis.

After MTF data is collected at Ambient, Hot, and Cold temperatures, it is then analyzed for benchmark performance against the design limits. Shown in Fig.71 is the Hot test performance for multiple prototype cameras across multiple fields of view. Data shows that none of the prototypes have degraded MTF below the design goals in all regions of interest across all fields of view. The same analysis with the same conclusion is shown in Fig.72 at cold temperature.

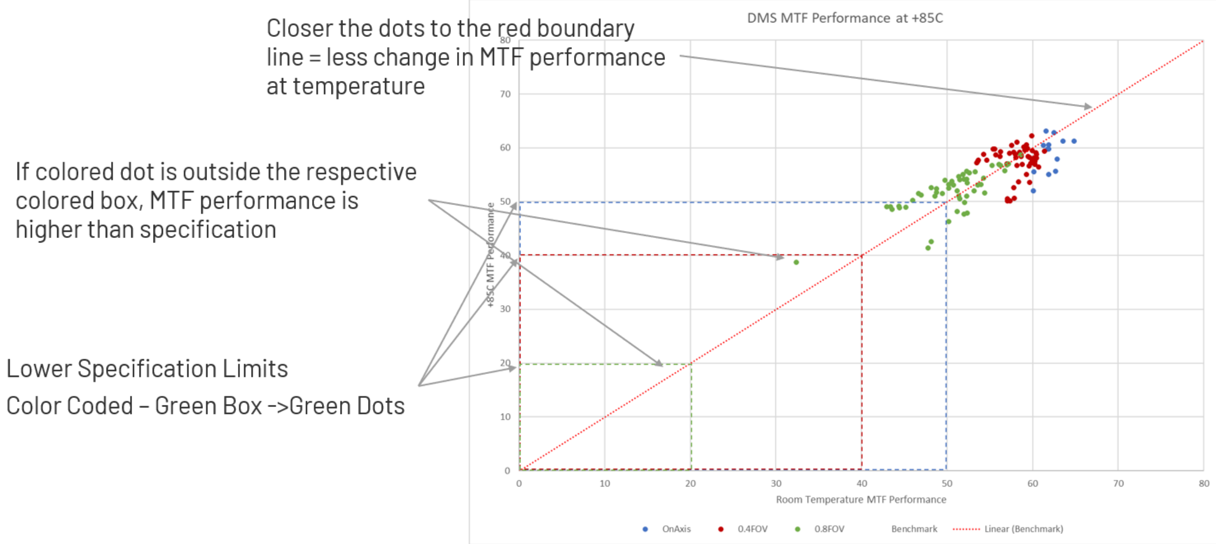


Figure 71 - Final design MTF Performance at Hot Temperature.

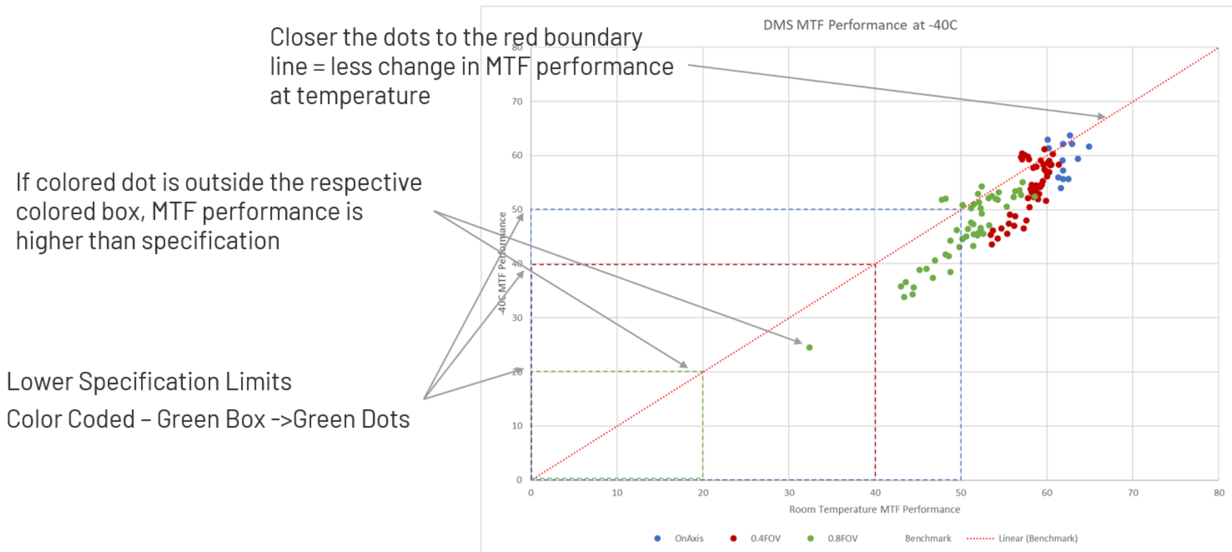


Figure 72 - Final design MTF Performance at Cold Temperature.

The sixth, and final part of the analysis is the evaluation of the manufacturability of the design, as well as capability of the design to achieve the same performance in mass manufacturing as with first prototypes. Shown in Fig.73 is the Hot and Cold Performance Capability analysis for OnAxis Field of View. Results show that Cpk of the camera distribution is 1.57, which is slightly lower than the minimum design goal of 1.67. This means that design tolerances for prototypes are out of range, and when manufacturing tooling is made, it will be required to be adjusted until Cpk performance is higher than 1.67.

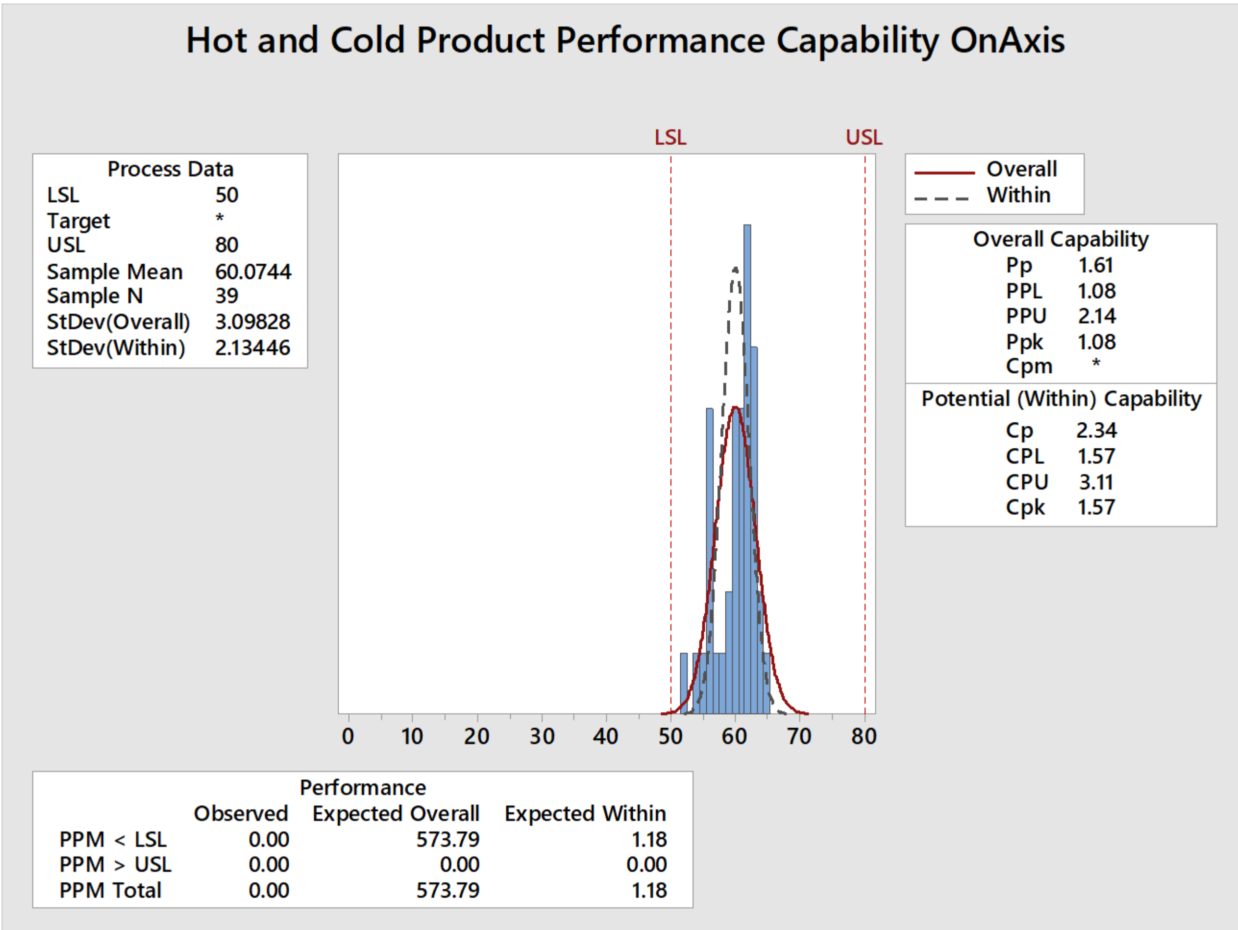


Figure 73 - Final design Hot and Cold Performance Capability OnAxis.

The same performance analysis was performed for 40% (shown in Fig.74) and 80% (shown in Fig.75) Fields of View. Both fields exceeded the Cpk design goal and will not require tolerance adjustments in lens assembly and manufacturing process.

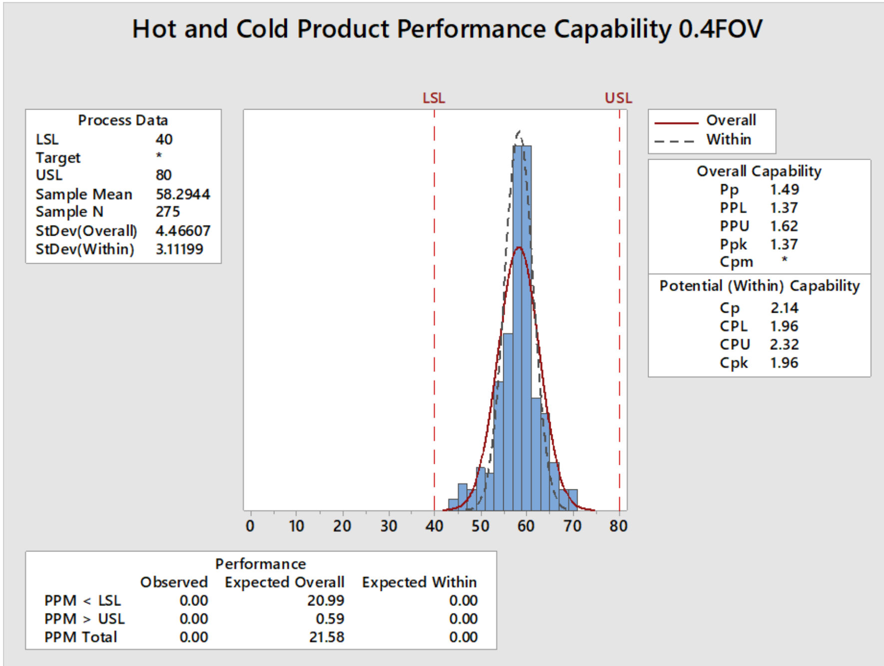


Figure 74 - Final design Hot and Cold Performance Capability 40% FOV.

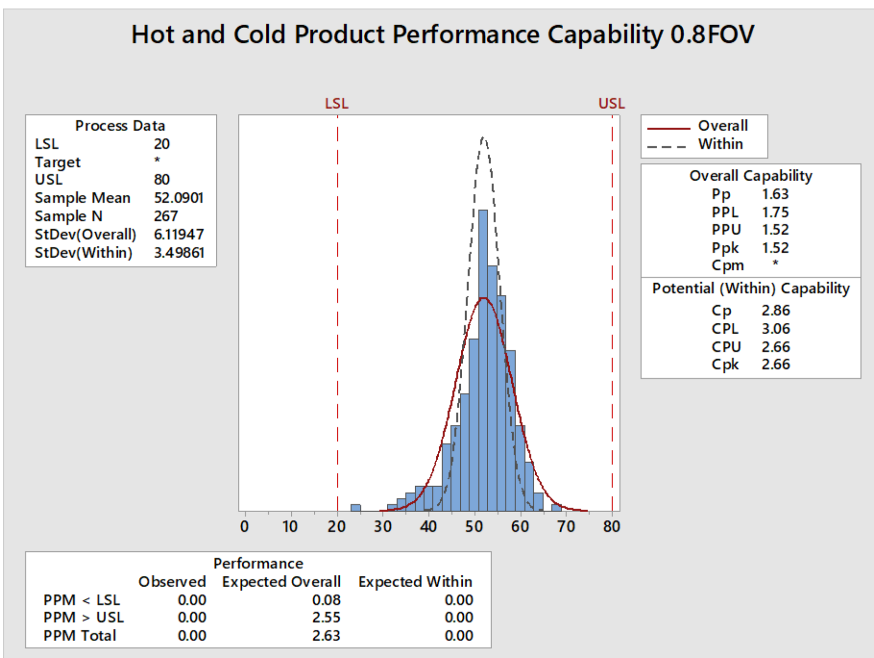


Figure 75 - Final design Hot and Cold Performance Capability 80% FOV.

6 Chapter 6 – Summary and Future Improvements

6.1 Summary of the DMS3 Design

DMS3 design consists of 3 parts – Lens, Imager, and Unibody Assembly. All design goals have been successfully achieved, as shown in Chapter 5. Lens design goals were to reduce the cost of the product by utilizing molded plastic elements, in addition to meeting performance requirements with an added 20% margin of manufacturing buffer for MTF.

Imager PCB design goals were to introduce the best in class QE performance imager in a minimalistic package to reduce the size of the product. This design goal has been achieved through removing serial interface and replacing it with a parallel interface as well as using a flexible connector cable.

Unibody Assembly design goals were to introduce an active Athermalization spacer, accommodate for same product parts to be able to support various FOV angles, as well as minimize overall size and number of required components. This part of the design has resulted in filings of three different patents. The first patent was the Athermalization spacer itself for automotive application. The second patent was the way lens barrel interacts with the athermalization piece. The third patent was the way imager assembly accommodates the same BOM components and different customer requirement angles.

After the design has undergone initial prototyping phase, analysis of the performance was complete, and shows that all design goals have been met.

6.2 **Future Improvements**

Future improvements of this design should include a more precise material match of the Athermalization portion of the design. This will allow for more loose manufacturing tolerances, achieving the same yields, and reducing the initial investment into the component supplier process.

Additionally, future designs could include more advanced manufacturing techniques for the lens, better materials, as well as better QE specialty image sensors, which would result in more efficient illumination and reduce the cost by minimizing the number and size of illumination components required to achieve performance.

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