Application Report

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Lenses for 3D Time-of-Flight (ToF) Image Sensors

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ABSTRACT

In a camera, the lens ensures that light coming from a given point in a scene reaches a given pixel. When an ideal lens is in perfect focus, light coming from a given point in the image will reach a given pixel only. This is an important optical component which enables cameras, including 3D time-of-flight (ToF) cameras, to work. 3D ToF cameras have certain distinct characteristics which have special requirements to be met with while selecting or designing the lenses. This document explains how to decide the specifications for 3D ToF cameras. It also describes how to choose or design lens holders.

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Trademarks

1 Background

Detailed information on 3D ToF cameras is given in *Time-of-Flight Camera – An Introduction* (SLOA190). This document describes the specifics which set the 3D camera optics requirements distinct from conventional cameras.

A 3D ToF camera works on active lighting only. It cannot get any depth signal from the ambient light. So it is important that the light collection ability of the lens is as efficient as possible. The light collection ability of the lens depends on the lens aperture and the transmission efficiency in the wavelengths of interest. The range of wavelengths the user would be interested in is the transmission spectrum of the LED or Laser being used for the camera. The effective light collection ability of the lens is not the same for each and every pixel. It reduces as you move farther and farther from the center of the lens optical axis. This specification is called relative illumination. For applications requiring good performance at the edges and corners of the scene, relative illumination is an important specification.

In order to optimize the camera, the light power incident on each pixel has to be maximized. More light power on the pixel provides a larger signal power. This increases the *Signal-to-Noise Ratio* (SNR) of the system resulting in an improved depth resolution. Lenses with the largest absolute aperture do not necessarily give this.

The mathematical relations need to be carefully derived. If the constant light intensity on the target is I, then the per pixel light power, P is given as:

$$P \propto \frac{I\mu^2\eta}{(f^2/A^2)}$$

where

- I = Light intensity on the target (W/m2)
- µ = Pixel size (m)
- A = Lens aperture (m)
- η = Lens transmission efficiency
- f = Lens focal length (m) (1)

Among these parameters, I is purely dependent on the illumination and the object distance and µ is dependent on the sensor. In the camera design, the lens design can affect in terms of the F number and the transmission efficiency.

2 Lens

An example lens specification which works well for a 3D ToF system is shown in Table 1.

Table 1. Lens Specifications

Specification		Value	
Sensor Format	Horizontal	80	pixels
	Vertical	60	pixels
Sensor Pixel size	Horizontal	30	um
	Vertical	30	um
Light Wavelength		850 nm	
Effect Focal Length (EFL)		1.62 mm	
F.No		1.2	
Transmission efficiency		>85% @ 850 nm	
		>80% @ 835 nm to 870 nm	
		>70% @ 800 nm to 900 nm	
Lens Total Length		<10.0 mm	
View Angle	Horizontal (deg)	75°	
	Vertical (deg)	57.4°	
	Diagonal (deg)	90°	
Resolution (MTF)	On Axis	> 70% contrast at 17 lp/mm	
	Full Field	> 50% contrast at 17 lp/mm	
	TV distortion (Trad.)	< 10%	
Relative Illumination (Ref.)		70%	
Chief Ray Angle		< 10%	
Maximum Image Circle (MIC)		3.6 mm	
Back Focal Length		1.0 mm	
Barrel Thread Size		M12 × 0.5	

Detailed information on each of these topics is freely available on the internet. This document deals only with the specifications important to the topic.

2.1 F Number:

The F number is the ratio of the focal length (f) to the aperture (A). This is a common way of specifying the aperture of the lens.

$$\text{F number} = \text{Focal length} / \text{Aperture} \quad (2)$$

The pixel light collection power scales as a second power of the F number. It is important to have a very low F number to get the largest aperture possible.

The low F number has other side effects to account for. Low F number lenses have a very narrow depth-of-field owing to the large aperture sizes. Depth-of-field is the range of distances over which the camera appears to be in focus. The lens depth-of-field must be carefully designed considering the application for the camera. The limits of lens depth-of-field should match or exceed the minimum and maximum distance requirements of the final cameras that the lens would be used in. Depth-of-field increases as the pixel size increases. TI's 3D ToF sensors have pixel sizes larger than usual RGB camera sensors. Owing to the larger pixel size, the OPT8241 will have a very wide depth-of-field compared to a typical RGB camera for the same lens.

2.2 Transmission Efficiency

Transmission efficiency depends largely on the *Anti-Reflective Coatings* (ARC) used on the lenses. Typical lenses for visible light have ARC which are wide-band in nature. Lenses for ToF cameras need to work for only a narrow range of wavelengths. This makes the ARC more “monochromatic” (narrow band) in nature. As a general rule, it is possible to make ARCs with better transmission efficiencies for a smaller range of wavelengths. So if a lens has 85% transmission efficiency for a visible range of wavelengths, it should be possible to change the coatings on the lens elements to have transmission efficiency better than 85%.

3 Lens Holder

Lens holder is the component which holds the lens to the PCB. This has to be designed or selected considering the mechanical dimensions of the lens.

3.1 Thread

The lens holder should match the thread diameter and the thread pitch of the lens. An example metric thread specification is M12 × 0.5. This means that the thread is of 12 mm diameter and 1 full rotation of the lens in the holder would move it vertically by 0.5 mm.

3.2 Back Focal Length

The holder should have clearance for the lens *Back Focal Length* (BFL). Back focal length of the lens is the physical distance between the bottom of the lens barrel to the top of the sensor in air. The concern is that the holder might not have enough clearance to allow the lens to screw in all the way to come in perfect focus. It is also possible in some rare cases that the holder does not have enough thread length to allow the BFL of the lens. Sensor cover glass will have a refractive index greater than 1. So the equivalent path length in air has to be considered as BFL for the actual physical distance between the lens and the sensor package glass top. Example calculations follow:

Sensor package glass thickness, d: 0.5 mm

Sensor package glass refractive index, μ: 1.5

Lens BFL (specified in data sheet): 3.03 mm

Path length required = 3.03 mm

Path length inside the cover glass = $\mu \times d$ = 0.75 mm

Net physical distance from sensor = BFL – $(\mu - 1) \times d$

Physical distance from cover glass = BFL – $\mu \times d$

3.3 Centering

The sensor need not have its optically-active pixel area in the center of the package. For instance, the OPT8241 has its pixel area off-centered.

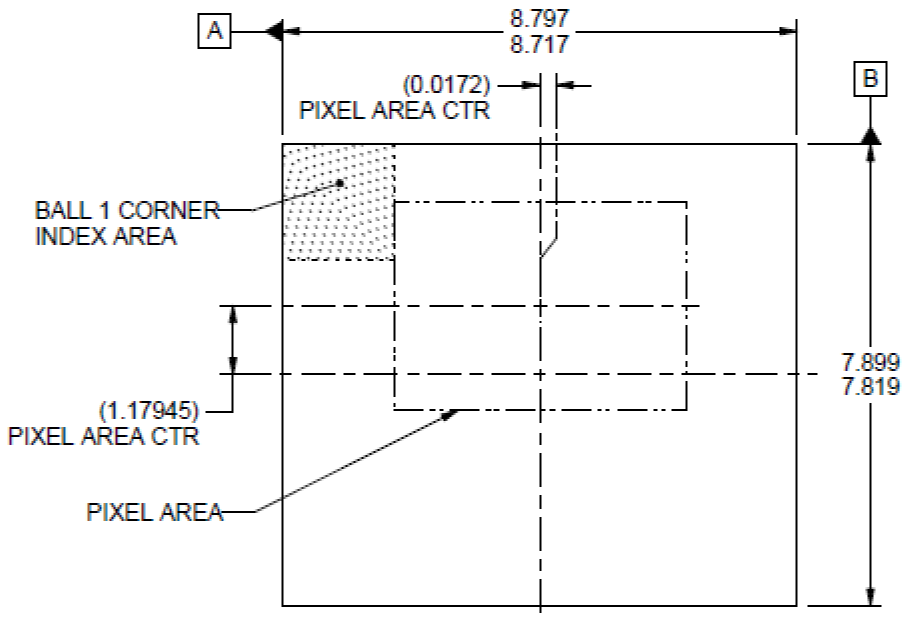

Figure 1. OPT8241 Pixel Area

The lens optical axis has to pass through the pixel area's center. This might involve using lens holders which have an offset in the lens optical axis. It is also possible to use much larger lens holders which still manage to encompass the sensor package under them.

There might be other components present around the sensor package as well. AC decoupling capacitors and other such components which have to be placed very close to the sensor package will have to be accommodated under the lens holder. The holder has to be chosen or designed for the PCB footprint area taken up by the components as well as the profile height of the components. Some taller components might not fit under the lens holder.

Another important aspect with respect to centering is the centering tolerance of the lens holder. Typical mounting by making use of screws might help center the lens up to a tolerance of ±100 µm. In the OPT8241, 13 pixels are 200 µm. It gets progressively harder to correct for the lens distortions and the mounting tolerances as the centering goes off. Use lens holders with good centering. Sometimes this is done by using alignment tabs.

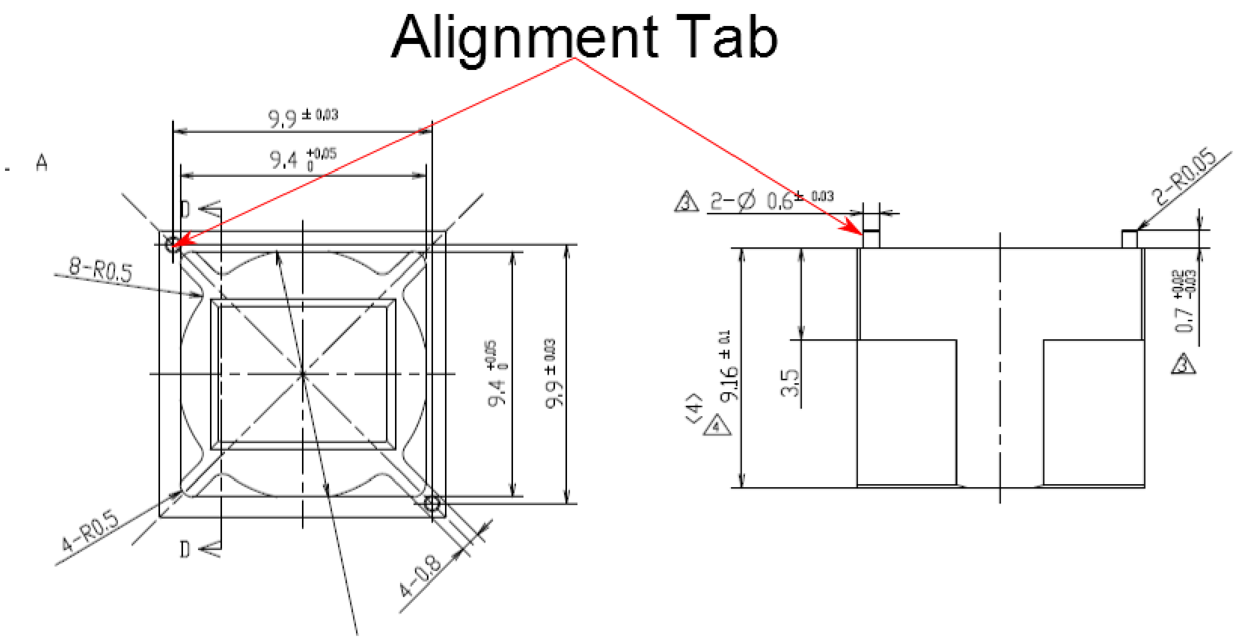

Figure 2. Lens Holder

These alignment tabs get inserted into high precision holes made in the PCB. Unlike screws, these can be made to fit tightly inside the PCB. The alignment tabs give much better centering as compared to screws. Screws will still be useful as an alternative to glue to affix the holder on to the PCB.

4 Summary

This document described the following:

- Details on the optic selection for 3D ToF cameras
- Difference in the lens requirements for 3D ToF cameras and typical cameras
- Basic concerns while designing or choosing lens mounts for a given lens

Very few lenses available in the free market fit the requirements of 3D ToF cameras. It is useful to identify sources of compatible lenses and share it with the community. Usually these sources would be geared to supply small quantities. Sharing the lens source with the community would help drive prices down by increasing volumes.

IMPORTANT NOTICE FOR TI DESIGN INFORMATION AND RESOURCES