RUGGEDIZED LENS METROLOGY

Edmund Optics®
WhitePaper

TESTING STABILITY RUGGEDIZED IMAGING LENSES

Stability ruggedized lenses can maintain their optical pointing after exposure to environmental shock and vibration. This pointing advantage can increase the accuracy in calibrated imaging applications such as measurement and gauging, 3D stereo vision, robotics and sensing, autonomous vehicles, and object tracking. For example, many 3D imaging systems rely on calculating the centroids, or geometric centers, of the objects in the devices' field of view. Centroiding algorithms are sensitive enough to determine positions smaller than one-tenth of the sensor pixel size [1]. This means that very small motions of lens elements due to vibration and shock can cause an imaging algorithm to lose accuracy or go out of calibration.

A shock is any kind of short duration, high acceleration loading on a system. Shock loading is usually specified in G's, or multiples of acceleration due to gravity (9.81 m/s^2). Typical shock loads can range from 10 G's to well in excess of 50 G's. In most applications, the duration of the shock is just as important as the magnitude for developing specifications. For example, astronauts typically experience a sustained 3 G's of acceleration during a launch, however the shoc experienced by a lens when it is dropped a few inches onto a tabl can easily exceed 20 G's.

Edmund Optics offers three types of ruggedization in our fixed foca length imaging lenses: Industrial Ruggedization, Ingress Ruggedization, and Stability Ruggedization. Here we explore the advantages c Stability Ruggedized lenses in preventing image shift due to harsh environments, such as those found in high volume manufacturing or in the body of an aircraft (*Figure 1*). This includes a look at the root cause of pixel shift, and outlines the challenges of indirectly measuring very small lens motions.

Figure 1: Examples of environments where ruggedized lenses are ideal for maintaining performance through shocks and vibrations.

What is Pixel Shift?

Pixel shift occurs when individual lens elements in a system move with respect to the assembly. The lateral motion of these elements will cause the outgoing image to shift both in position and angle. The amount of shift scales with the magnification of the lens:

$$\Delta x_l = \Delta x_i * (1 - m) \quad [2]$$

where Δx_i is the magnitude of image shift on the sensor, Δx_l is the magnitude of the lens element shift in the lens barrel, and m is the magnification of the lens element as it relays the image through the system. Inside a lens assembly with multiple elements, these effects can accumulate as they propagate through the system. *Figure 2* shows how this effect can stack up. It is important to note that both the top and bottom system can still meet other system level specifications such as MTF. This is because all optical systems are designed to perform "as-built", that is, when considering the tolerances between the lenses and barrel.

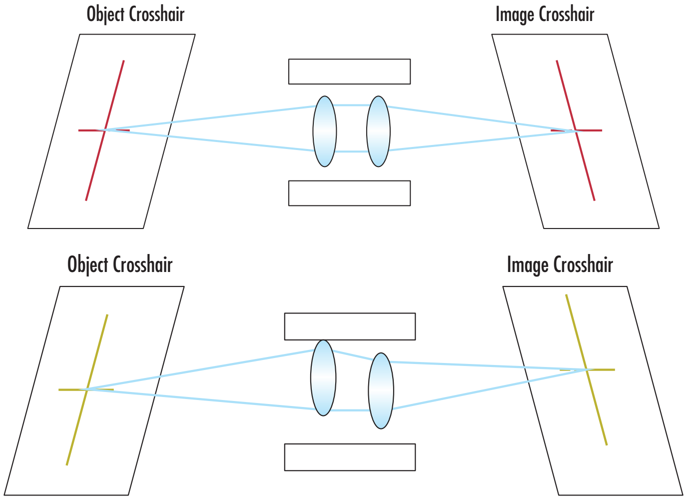

Figure 2: Diagram of image shift for a lens system. Top: An undisturbed image system. Bottom: a shifted image as a result of a shifted lens element.[3]

In a typical optical assembly, resistance to shock forces is governed by Newton's second law of motion, which states that acceleration is proportional to mass. In a standard lens barrel, a retaining ring provides a preloading force to a lens, and the force of friction keeps this lens in place. This is stated mathematically as:

$$P = \mu \times M \times \alpha_{max}$$

where P is the preload, μ is the coefficient of friction between the lens and the retaining ring, M is the mass of the element, and α_{max} is the maximum acceleration that the lens element can experience before it moves. This equation has some predictive drawbacks in that it can be difficult to correctly estimate the preload and friction coefficient.

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Instead of relying on friction, Edmund Optics ruggedized lens offerings take things one step further by potting the lenses in place. An adhesive bond of each lens element to the tube dampens vibrations, distributes forces, and constrains the lens in place. For the TECHSPEC® Cr Series Fixed Focal Length Lenses, "ruggedization" refers to image stability rather than just survivability (which is the resistance of a lens to gross failure, such as a cracked element).

How Small Does Pixel Shift Need to Be?

In 3D imaging applications, centroiding algorithms are sensitive enough to determine positions smaller than one-tenth the sensor pixel size [1]. This means that the pixel shift an imaging system must maintain has to be smaller than 3-5µm (size of a typical pixel). Edmund Optics Cr Series Fixed Focal Length Lenses achieve pixel shifts smaller than 1µm after withstanding 50G of shock *(Figure 3)*.

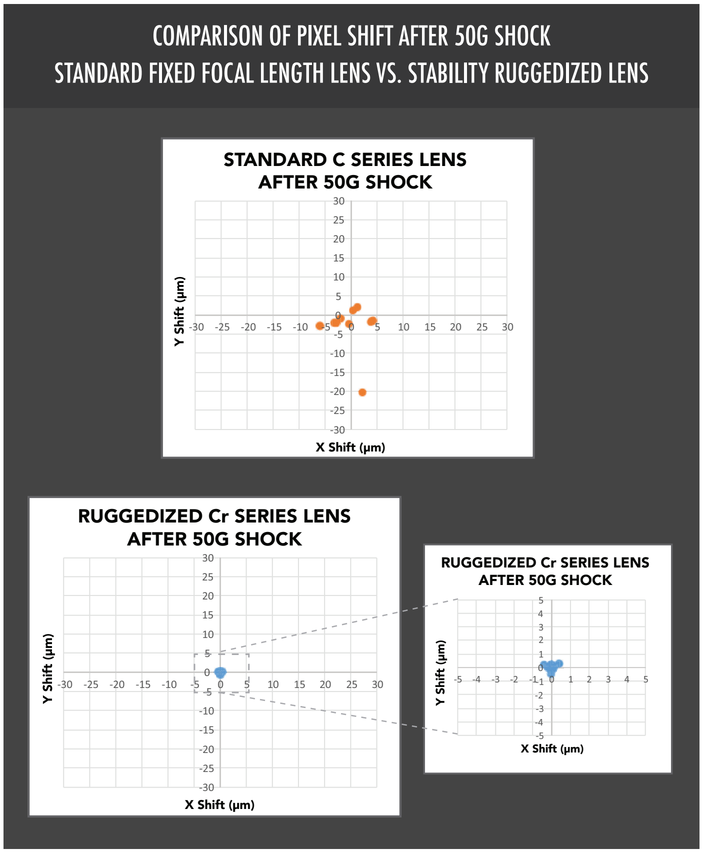

Figure 3: While the standard imaging lens (C Series Fixed Focal Length Lens) on the left performs well under normal conditions, 50G of shock causes a pixel shift of more than a single pixel. The Stability Ruggedized Cr Series Lens, on the other hand, experiences less than 1µm of pixel shift after 50G of shock, which is a much smaller shift than the size of a pixel.

Quantifying Shock

Usually, shock is thought of as a high acceleration event. A more complete picture however, is to consider not just the peak acceleration, but also the time duration of the shock. On a rollercoaster ride, you might experience G forces between 4-6 G's. When dropping a lens a few inches onto a hard metal table, the lens might experience accelerations between 20-50 G's! The difference is the duration of the acceleration. If a shock event overcomes the preload on a lens for even a few milliseconds, a lens element may still move freely and displace by a few micrometers.

In all Edmund Optic's testing, ruggedized lenses are subjected to 50 G's of shock for a period of 2ms.

How to Test for Stability Ruggedization?

Edmund Optics ruggedization testing is split into two stations. The first station is an imaging system which can measure the location of a focused spot to within ± 100nm. The second station is a drop tower which administers a shock to each lens. Testing for pixel shift of less than 1µm is no simple task, as 1µm is smaller than a particle of dust. The test system for pixel shift has to be very sensitive, repeatable, and accurate. Each ruggedized lens is screwed into a kinematic mount for the duration of the testing to repeatedly transfer the lens between stations. A major design challenge was to make the kinematic mount repeatable enough that the lens can be transferred from the imaging system to the shock tower without altering the measurement. This mounting method achieves measurements with precision better than 200nm, $\frac{1}{17}$ the size of a 3.45µm pixel.

To test a lens under shock loads, this instrument must also be impervious to these same shock loads. Our testing revealed that just like dropping a lens on a table, even the acceleration of transferring the kinematic mount between stations could exceed 20 G's! These accelerations are extremely short lived, less than 1ms. However, the acceleration is high enough to overcome the static friction between any bolted interfaces and can cause microscopic shifts in the test apparatus. To overcome this challenge, the instrument employs a mounting system that gently brings the kinematic mount into contact with the imaging station with a shock force less than 3 G's.

Considering the C-Mount

Edmund Optics Stability Ruggedized Cr Series Fixed Focal Length Lenses are designed to ensure that the lens elements do not move within the housing. It is also important to ensure that the lens housing does not move relative to the camera. The interface between the lens and camera can be an area of failure under shock and vibration.

Edmund Optics has tested and recommends two solutions for preventing shift between the lens assembly and the camera:

1. A modified camera C-mount that includes a nylon tipped screw to grip the threads on the lens
2. A medium-strength adhesive applied to the C-mount thread interface between the lens and camera

Edmund Optics Stability Ruggedized Cr Series Fixed Focal Length Lenses feature a stainless steel C-mount clamp. We recommended that users tighten the clamping bolt to a torque of 8-10 in-lbs. This ensures focus and working distance are locked in place while preventing the lenses from shifting within the C-mount.

When trying to maintain calibration and reduce the amount of potential pixel shift, there are many moving parts to consider. The lens elements can move inside the barrel – this is addressed by gluing each element in place. The focus mechanism which provides working distance adjustment can shift if it is not tight enough. The lens to camera C-mount interface can also shift. If any one part of the mounting in the imaging system overcomes static friction, even on a microscopic scale, alignment and calibration may be lost, potentially resulting in false data.

When considering image shifts far smaller than a single pixel on a camera, Edmund Optics addresses lens shift, mechanical drift, as well as the challenge of testing a Stability Ruggedized lens. TECHSPEC® Cr Series Fixed Focal Length Lenses integrate our solutions to these challenges for superior performance in high shock applications.

References

1.) Quine, Brendan M., et al. “Determining Star-Image Location: A New Sub-Pixel Interpolation Technique to Process Image Centroids.” *Computer Physics Communications*, vol. 177, no. 9, 2007, pp. 700–706., doi:10.1016/j.cpc.2007.06.007.

2.) Schwertz, Katie, and Jim H. Burge. *Field Guide to Optomechanical Design and Analysis*. SPIE Press, 2012.

3.) *Ruggedization of Imaging Lenses*. Edmund Optics, 2017, www.edmundoptics.com/document/download/416052.