

MAXIMUM OPTICAL PERFORMANCE BEYOND 1.1" SENSORS

More and more industrial sensors are growing beyond the 1.1" form factor size thanks to increased resolutions. In addition, pixels are getting smaller, making the sensor more sensitive to optical path tolerances. To match these growing sensor trends, the TFL-Mount, as found on the CA Series Fixed Focal Length Lenses, brings a standardized, compact, high-performance design, specifically targeted for APS-C and 4/3" sensors.

Filling the Gap Between C-Mount and F-Mount

While the ability to design and manufacture more precise optical components is always improving, the fundamental lens technology continues to rely mostly on refracting light with glass. It is now commonplace to see industrial sensors with over 20MP resolution at a reasonable price and with good performance, all packed into a C-Mount camera. However, as sensors continue to increase both in size and resolution, the C-Mount standard is reaching its limit with respect to APS-C and 4/3" sensor sizes; the sensors are simply too large for the C-Mount opening. While F-Mount and M42 lenses

offer a possible solution for such sensors, they come with drawbacks. To address the gap between C-Mount and F-Mount, the TFL-Mount is a great option.

There are three ways that sensors can increase resolution: the size of a sensor can grow while pixel size remains the same, pixel size can get smaller while sensor size remains the same, or both (*Figure 1*). There are tradeoffs with each of these methods; typically, smaller pixels tend to mean a lower signal to noise ratio (SNR) when compared to larger pixels, but larger sensors tend to be more expensive. The general trend, however, shows sensor sizes increasing, even as pixels continue to decrease in size. The machine vision industry is at an interesting time currently, with sensor sizes maximizing the capabilities of a C-Mount. The C-Mount standard is defined by a 25.4mm threaded diameter mount with a back-flange distance (often referred to as a flange focal distance or simply flange distance) of 17.526mm.

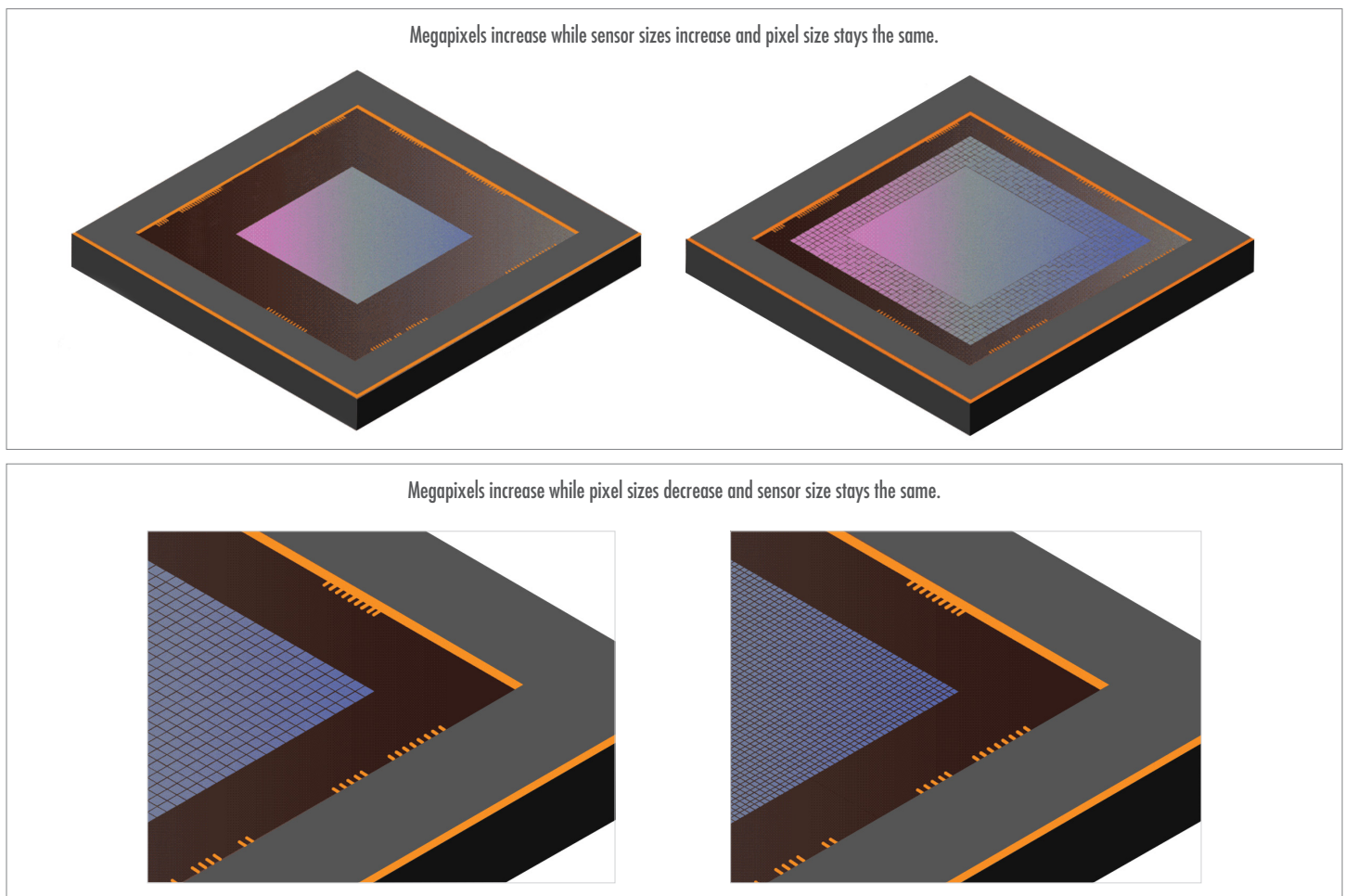


Figure 1: Sensors are increasing resolution by getting larger in size and by adding additional smaller-sized pixels.

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Reaching the Limits of C-Mount

As shown in *Figure 2a*, below, the maximum diameter that an optic can achieve in a C-Mount housing is around 17mm, despite the mount opening being 25.4mm. This is because the lens assembly has mechanics of its own that must accommodate the main lens barrel, the focusing inner barrel, and a retainer to hold the optical elements in place. Each of these features reduce the size of the available clear aperture of the optical elements in the lens assembly. As the size of the optical elements decreases, the angle at which the light must exit the lens increases. This is not a problem when sensors are smaller than the size of the optics, but as sensors increase in size, it becomes more difficult for the optics to be paired with the sensor inside of a C-Mount. As this angle (θ in *Figure 1b*) increases, the corners of the image become much darker due to $\cos^4(\theta)$ roll-off. *Figure 1b* shows this fall-off relationship with respect to the angle. In addition, the image sensor itself has roll-off associated with the way in which each pixel's micro-lenses are optimized. Because of this additional roll-off, it is of high priority to minimize this angle in an optical design. These combined effects essentially make the 1.1" format (17.6mm diagonal) the practical and limiting sensor size for best performance in a C-Mount camera.

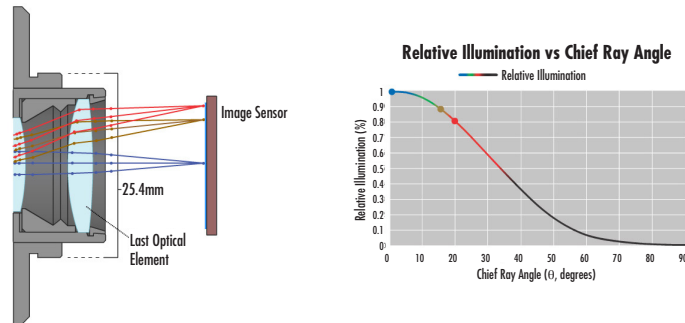
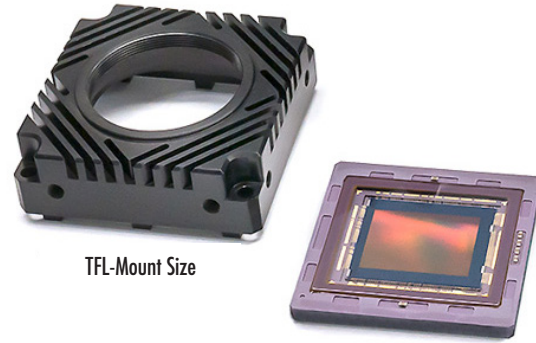


Figure 2: (a) Left: The cross-section of the back of a C-Mount, with a 1.1" format sensor and high-resolution 12mm focal length lens. Due to supporting mechanics, the maximum diameter of the last lens element is smaller than the 25.4mm C-Mount opening. This results in steeper ray angles for larger sensors, which can affect brightness (above right graph; red lines represent light rays for the corner of a 1.1" format sensor, brown lines represent 1" sensor, and blue lines represent the sensor's center). (b) Right: The impact of chief ray angle on relative brightness on an image sensor. Steeper angles reduce brightness on the sensor edges unless mitigated with more costly optics. Large sensors in C-Mount cameras exacerbate this problem.

The IMX342, which is a 31.4MP sensor in an APS-C format (27.9mm diagonal) came with the third-generation release of Sony's Pregius. This sensor is far too large for a C-Mount. However, it is in an interesting space for the industrial camera marketplace, as this sensor is too small for an F-Mount (M42), which is the next size up and has several optical problems associated with it. M42 is a potentially logical option, and cameras already exist with an M42 lens mount, though there exists no commonly accepted standard to which the camera industry adheres to make this option viable (with varying flanges and thread pitches). However, TFL is the perfect mount for a sensor of the APS-C size and is standardized through the Lens Working Group of the Japan Industrial Imaging Association (JIJA). A TFL-Mount is M35 × 0.75 mm, with a 17.526mm flange distance; this is the same flange distance as the C-Mount. Because of this, it can be thought of as a larger diameter C-Mount.



TFL-Mount Size

31.4MP, Sony IMX342 CMOS
Sensor Size: APS-C 27.9mm

TFL-Mount vs F-Mount

The TFL-Mount has several advantages over the F-Mount for an APS-C sensor size. These advantages are in cost, flange distance, and the way that the lens is secured into the lens mount on the camera. F-Mount lenses are larger compared to TFL-Mount lenses. This is mostly because they are meant to cover much larger sensors (up to 43.3mm diagonal vs APS-C 27.9mm diagonal). As lenses increase in size, they become more expensive as well; a rough rule of thumb would indicate that the cost for a single lens element grows with the radius squared. Extrapolated over several elements, it is easy to see how larger lenses are more expensive.

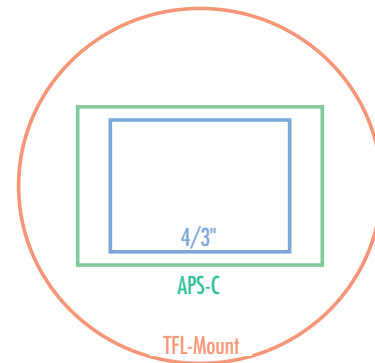


Figure 3: The TFL-Mount gives enough space for surrounding lens mechanics for APS-C sensors, which reduces issues created from steep ray angles.

Flange Distance Matters

Another major advantage of the TFL-Mount solution over an F-Mount solution is the flange distance. As mentioned above, the TFL-Mount can be thought of as a larger diameter C-Mount because they share the same flange distance of 17.526mm. F-Mount has a flange distance of 46.5mm. The long flange distance of the F-Mount limits the type of optical design form that can be used. This is especially true for shorter focal length lenses, which tend to have shorter back focal lengths (BFL, not to be confused with a flange distance, the back focal length is the distance from the last optical element to the image plane).

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Making a short focal length with a long BFL forces the lens to be designed as a reverse telephoto, which is to say a lens with a focal length that is longer than the overall length of the lens. Forcing a lens into this design paradigm inherently causes resolution tradeoffs. In certain circumstances, this can be overcome with lenses that have a larger rear protrusion (the lens protrudes into the camera housing). However, lenses with large amounts of rear protrusion tend to need to be reduced in diameter substantially to properly fit inside the camera body, leading to the same $\cos^4(\theta)$ issues listed above. The shorter flange distance of the TFL not only contributes to an overall shorter system, but also allows the optical engineer considerably more design freedom to maximize the resolution of the lens.

This smaller flange distance coupled with the fact that TFL lenses will be designed for smaller sensors and hence be less impacted by field-dependent aberrations, means that lenses designed for TFL-Mount cameras will perform better, in a smaller package size, and will be more cost-effective.

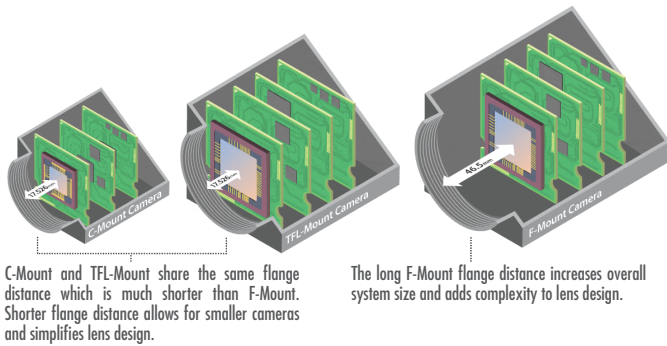


Figure 4: A camera cut-out illustration comparing the flange distance between C-Mount, TFL-Mount, and F-Mount and its effect on camera size.

Threaded vs Bayonet

F-Mount is not a threaded screw mount; rather, it is a bayonet mount. Bayonet mounts are great for photography, as they allow the user of the camera to swap lenses out quickly for different scenarios and allows for the easy integration of electronic features (iris/focus control) since they are a clocked mechanism. However, for most applications in machine vision, these features are not advantages. Lenses are rarely (if ever) replaced, and if they are, the replacement process is not in a time sensitive manner. Iris control is useful in corner case applications, but the $f/\#$ is usually fixed. Relying on servomotors/micro motors with moving parts to focus a lens in a factory environment millions of times is likely going to lead to parts wearing out.

The most impactful disadvantage of the bayonet mount is simply the nature of the bayonet mount itself. As sensors increase in size, the mount of allowable sensor tilt with respect to the optical axis becomes smaller. *Figure 6* shows how tilt in the image plane with respect to the optical axis impacts larger sensors more. Keeping the tilt aMount small is imperative to ensuring high optical performance, especially given low $f/\#$ s, which are required for high resolution applications. The bayonet mount allows for more tilt in the imaging system and does not pair the lens and camera together in an optimal way. This is mostly because the tolerances of the Nikon F-Mount are not published, so optics companies are left guessing what the tolerances should be for their designs. In contrast, threaded screw mount flanges are machined into a solid piece of metal and can be made very flat. Furthermore, the clamping force of threaded screw mounts are vastly stronger than a bayonet. The lens flange and camera flange are held flush together without wobble or sag even with vibration or gravity, regardless of the lens size. TFL is also a published standard and a threaded mount, meaning that both camera and lens companies know exactly what to design so that the camera and lens works together in the most efficient way possible.

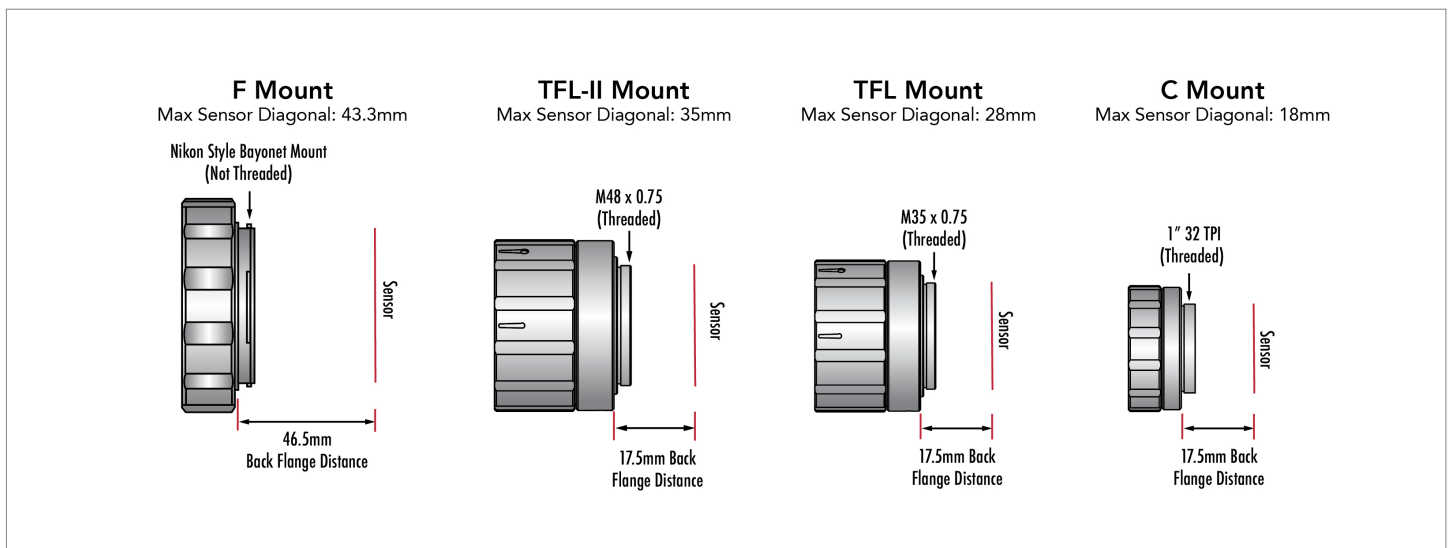


Figure 5: The TFL and TFL-II Mounts accommodate a larger maximum sensor diagonal.

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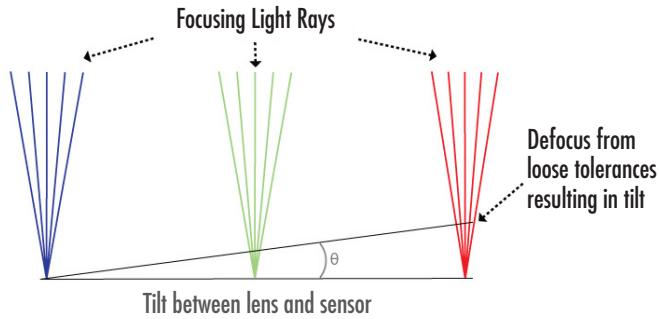


Figure 6: As sensors grow larger in size with smaller pixels, keeping tight tolerances are imperative. A bayonet lens connection is a looser connection to the camera compared to the TFL threaded connection. This could result in a less focused image.



Figure 7: Bayonet lens mounts are great for photography but their added components, multiple parts, spring-loaded clip connection, and lack of published specification standards introduces uncertainties for industrial applications needing 24/7 operation.



Figure 8: Threaded screw mounts (TFL lens shown above) are machined into a solid piece of metal allowing for vastly stronger clamping force with the camera. This eliminates wobble or sag even with vibration or gravity, regardless of the lens size. TFL is also a published standard.

TFL-Mount + Active Sensor Alignment

The perfect lens mount with the perfect lens will not mean much if the camera's sensor is not precisely aligned to the lens barrel. To maximize the value and performance of a high quality TFL lens with a TFL-Mount camera, active sensor alignment is needed to ensure that the sensors are centered and placed correctly within the camera, without tilt or rotation. This procedure is even more critical for sensors larger in size and with smaller pixel sizes, as these two characteristics make sensors more sensitive to micrometer placement discrepancies. As highlighted above in *Figure 6*, a tilt of only a few micrometers can effectively defocus a high-resolution lens on a large 4/3" or APS-C sensor.

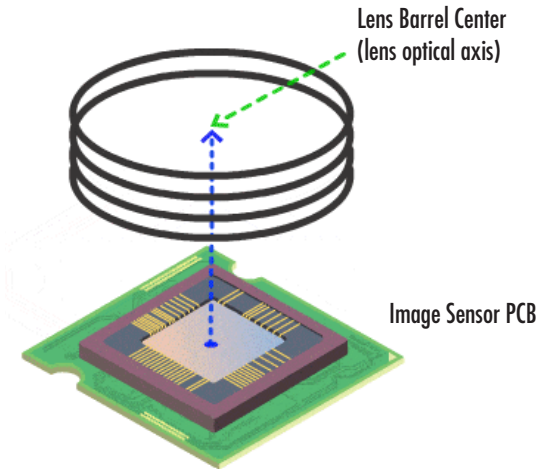


Figure 9: Active sensor alignment ensures that the sensor is centered and placed in the optimal position, without tilt or rotation, to the lens barrel. This ensures an optimal path for light to travel, through the lens to the sensor, with maximum sharpness from the center to the corners of the sensor.

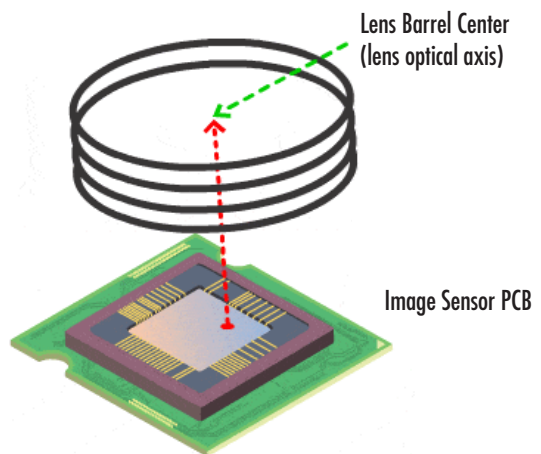


Figure 10: An exaggerated depiction of some of the variables encountered with camera components. This leads to inconsistencies with accurate sensor placement inside the camera.

TFL-Mount for Machine Vision Cameras

With TFL-Mount lenses being smaller, lighter, less expensive, and designed for long-term performance in industrial operations, they are certainly the better choice for sensors larger than 1.1" and up to APS-C size. While the standard is still gaining in popularity within the machine vision marketplace, they are a promising new take on the optics and cameras that are used every day. Sensors will, of course, continue to evolve, and camera lenses will continue evolving right along with them. More and more industrial sensors are entering the market beyond 1.1" and with smaller pixel sizes, such as Sony's 4th gen Pregius S 24.5MP IMX530 CMOS: a 4/3" sensor (diagonal 19.3mm) with a 2.74 μ m pixel size (37% smaller pixel size than the previous 3.45 μ m) as an example. These sensors will be best handled by pairing a high quality TFL lens with an actively sensor aligned TFL-Mount camera.