"In this whitepaper we are not going to focus on how to choose lens size, or what f-stop you need, but rather on how to choose the quality of the lens, which category of lens, and how much you should spend on the lens!"

How to Choose a Lens

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How to Choose a Lens!

As an independent distributor of a variety of seemingly similar cameras and lenses, we are constantly asked, 'What lens should I choose?'

The lens is at the front of the optical system. Without the proper lens, everything else that is specified behind the lens, the camera, the software, etc. might be moot! It's the old saying, 'garbage in, garbage out'. If you put a cheap lens on a high resolution camera, you can expect poor results!

What most of our clients don't realize is that lensing is part art, and part science.

In this whitepaper, we are not going to focus on how to choose what size lens you need or what f stop you need (though I will supply some necessary formula to calculate this), but rather on how to choose *the quality of the lens, which category of lens, or how much you should spend on the lens!*

<u>The Science.</u>
It is very easy to figure out what you need in regard to the focal length required. Here is the lens equation,

MAG = CCD size/FOV size

Focal length = Object Distance/ (1 + 1/MAG)

Angular FOV = 2 arctan (0.5 x Image Ht/Focal length)

Basically you need to know the size of the sensor (or size of the pixels and number of pixels), the field of view (FOV), and the distance the object is from the front of the lens. Plug these numbers in, and voila, you will get the focal length you need. Plus, you can find out your angular field of view.

We have a very quick focal length calculator on our web site at www.1stvision.com/focal.htm and another one on at our University of 1stVision page http://www.1stvision.com/university.htm . This is not a high end tool, but works for quick calculations. There are many other tools like this available on the web.

<u>What do lenses do?</u>
Basically, a lens magnifies (or de magnifies an image) according to the formula above.

Ex. You have a 10mm sensor, and your FOV is 1000mm. The magnification here is 1/100, so in this case we are taking a larger object and projecting it on a smaller imager. We are really de magnifying. So in this case you can say, 'you are REDUCING the object by 100'.

Ex2. You have the same 10mm sensor, and your FOV is 1mm. In this case, your magnification is 10. We need to take a small object and magnify to fill the sensor.

If you have magnification > 6, then what you really need is a microscope. (seeing small objects). Standard lenses work well from infinity to about 3x de magnification. Macro lenses work best with magnifications from ½ to 2. The remainder of this article will focus on 'standard' lenses.

<u>The Art.</u>

Lenses come only in a small variety of sizes. Standard lenses are available in 4, 6, 8, 12, 16, 25, 35, 50, and 75 mm focal lengths. So the science might have calculated that you need a 29mm lens. What do you do, choose a 25mm lens and have a wider angle picture, do you try to move your object closer, or do you pick at 35mm lens and move back. Or do you try to use extension tubes?

Further, say you choose the 25 mm lens. Now which brand; Fujinon, Tamron, Kowa, Navitar, Schneider, Edmundoptics, Rainbow, Computar, or Pentax (to name a few, but certainly not all). All these brands have 25 mm lenses. In fact, they all have several 25 mm lenses or varying quality. By the end of this white paper, we will have hoped to shed some light on which of these to choose.

<u>Extension Rings</u>

Lenses come only in discrete focal lengths, but many times your calculations require a focal length of something other than what is available. Lots of users think that is what extension tubes or rings are for. (Extension tubes or rings fit between the back of the lens and the front of the camera.) Well, sort of. If your calculations say you need a 30mm focal length, so you add a 5mm spacer to a 25mm lens, you do not have 30 mm lens, and you might NOT get the results you expect! You will get a smaller FOV with this setup than you would with just the 25mm lens, however, you will not get the same FOV as a 30mm lens, nor will you get the same magnification as you would with the 30mm lens.

Extension tubes do the following two things. 1. They change the range of focus and let you focus closer than the Minimum Object Distance (see next sentence). A lens focuses by moving the lens elements closer or further from the image plane. To get a close focus, you move the lens elements away. Lens are rated with a Minimum Object Distance or MOD. This is the closest the lens can be to an object and still be in focus. (BTW, lenses are designed to give the most optimal performance at infinity, not MOD). Once you twist the focus barrel so you are at its' closest focus stop, you cannot focus any closer. By inserting a tube between the back of the lens and the front of the camera, you are moving the lens further away from the image plane and can focus closer! 2. They decrease the field of view that you are looking at. Finally, if the ratio of the size of the extension tube to the object distance is significant, it will change the magnification of the system a bit.

Extension tubes come in sizes from 0.05mm to 20mm, usually in kits of 0.1, 0.5, 1, 2, 5, 10, 20, and 40 mm. Longer lengths can be achieved by screwing multiple sizes together. Once you add a significant amount of length, you will be able to focus much closer, but you will not be able to focus at infinity!

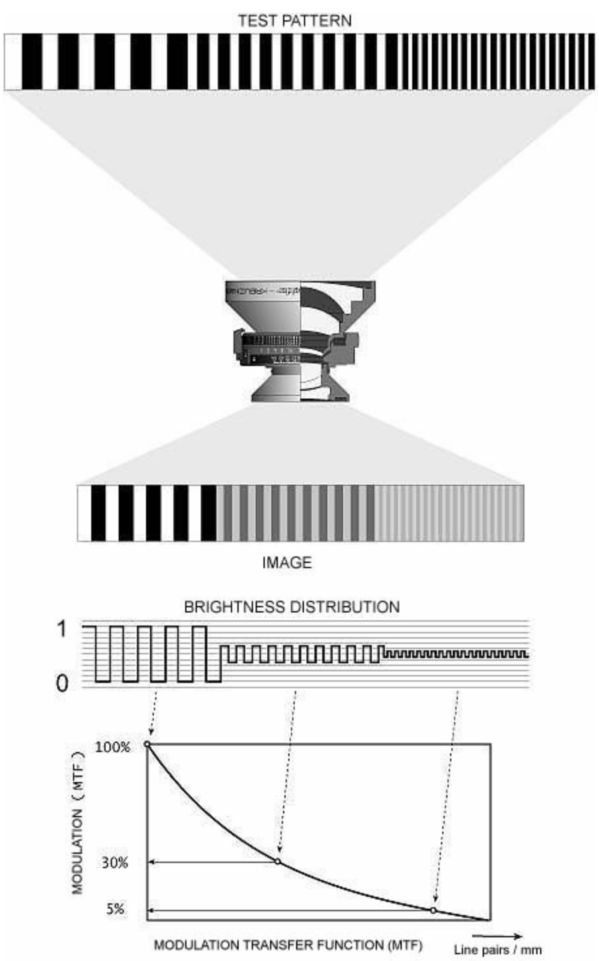
If you are mathematically inclined:

> Extension tubes work by moving the lens further from the film than the focusing mechanism alone can handle. The basic optical formula is as follows:
>
> $1/f = 1/f' + 1/f''$
>
> Where f = the nominal focal length, f' = the distance from the image plane to the rear node, and f'' = the distance from the front node to the object.
>
> $f' = f + e$
>
> Where e = the total extension (including the focusing helix and extension tubes).

If not, use the following link: http://www.1stvision.com/lens/extension_tubes.htm

How to rate a lens: MTF.
This is very simple in theory. The modulation transfer function , also known as MTF gives you the performance of light through a medium. It compares the intensity of the light before the optics vs. the intensity of the light after it goes through the optics. This is not a single number , but rather it varies as light hits the lens on or off axis, and is also dependent upon wavelength of the light. MTF is normally given in line pairs/mm or lp/mm vs. % transmission. Essentially, it tells you how well the lens can resolve a certain size spot. If you draw lines that get closer and closer together, at some point the optics system is going to see the 2 lines as a single blurred line. This is basically where the lens breaks down, and this is just past the limit of its resolving power. In the diagram below you can see as the lines get closer together, the intensity fades. (picture courtesy of Schneider Optics)

Note: some lens manufacturers give MTF as only lp/mm and not vs. % transmission. E.g 60 lp/mm. This does not mean that you cannot see objects smaller than this MTF, it is just that the intensity of the image is lower than 100% at this rating. As the intensity drops at some point your eye or the processing SW can not distinguish between line pairs.



The total MTF is derived from a multiplying all the MTFs of the system. This would include the MTF of the lens, the filter, the camera, the electronics, etc.

So if you have a megapixel sensor with a high MTF, but put a cheap lens in front, you have degraded the MTF of the system. Garbage in, garbage out!

The problem with MTFs.

The problem is that most of the lens manufacturers listed above do not supply MTF information, or do not supply complete MTFs. Lens manufacturers with high quality optics, such as Schneider provide a complete set of MTFs vs. transmission.

Can I just measure the MTF myself?

The short answer to this is: Not so easily! First off, the MTF of a computer monitor is probably around 30 lp/mm. All the lenses we are discussing in this article are at least 2x this, if not 3 or 4x it. So the limiting factor is the monitor, and you will not be able to see any differences. If you have a resolution chart, and some software where you can get the actual pixel data and plot it vs. the test pattern, you can get a better idea. However, a fairly rigid test set up with constant lighting, constant exact FOV and other identical parameters is needed. Not something you can just whip up in a few minutes or hours. Optical testing is correct way to do this!

Bottom Line: You are not really going to be able to 'see' (by this I mean you personally will not be visually able to see) the difference between lenses within the same class, nor will you normally even be able to see the difference between lenses of different classes unless you have a very precise optical setup. So if you think you can compare MTFs of different lenses by just placing a printed lens chart on the wall and putting the camera on a tripod a few feet away and looking at the image on a computer screen: **NO WAY!**

However, the computer can 'see' the differences!

For a complete article on MTFs, we refer you to
http://www.optikos.com/Pdf_files/how_to_measure_mtf.pdf

Megapixel lens ratings, the myth.

Until about the year 2000, it was very rare to have a megapixel CCD camera for industrial automated inspection applications without spending many thousands of dollars. The 'standard' resolution was VGA, in fact the big jump only a few years earlier was to progressive scan camera with VGA resolution. Megapixel cameras at the time were usually full frame cameras, with very large sensors, requiring very large lenses.

Sony introduced a 2/3" megapixel sensor in the late 1990s which started a trend towards low cost megapixel CCD sensors. Since then, you can get machine vision quality megapixel cameras for about $1,000 - $1,500. Multi megapixel cameras are within 2x that range.

What this meant was that lenses that used to be good enough for 640 pixels across now needed to be able to resolve 1280 pixels across, and after that, 1600 pixel, and now, 2048 pixels.

So lens manufacturers have come out with a new line of lenses dubbed ‘megapixel lenses’. This is supposed to indicate that they are good for megapixel cameras.

However, a lens’ resolving power is based on how small a spot (usually this spot is the minimum size of the objects characteristic) it can resolve. It is rated in lp/mm. So if you want to resolve an object that is the size of of a single pixel for a particular sensor, what is really needed is the size of the pixel, and then plug it into the formula below. This will then give you how many lp/mm you need to resolve a pixel of that size.

The resolution limit of the sensor (Nyquist Frequency) is:

0.5 x 1/pixel size(in mm) = lp/mm to resolve

Therefore, it is not the number of pixels that is important, but rather what the size of the pixel is that determines the quality of the lens that is needed!

So saying that a lens is a ‘megapixel’ lens is really meaningless!

The number of pixels is only relevant if the size of the sensor stays the same when you increase the number of pixels. This relationship would decrease the size of each pixel, and therefore require you to have a higher quality lens.

<u>Example</u>: For the following pixel sizes, you would need a lens with the following ratings to resolve a single pixel (plug pixel size into formula in box above):

6.5um pixels = 77 lp/mm
4.5um pixels = 111 lp/mm
3.6um pixels = 138 lp/mm

<u>Example</u>. The Sony ICX 285 sensor is a 2/3” sensor with 1390 pixels across. Each pixel is 6.5um. Sony makes the ICX 267 with an identical number of horizontal pixels, 1390, BUT the sensor is a ½” sensor, and the pixels are 4.65um.

Both are ‘megapixel’ sensors, both with equal number of pixels across and down.

However, the ICX 267 sensor with the smaller pixels requires a higher quality of optics to resolve a single pixel!

A specific ‘megapixel’ lens will NOT perform the same on the same resolution camera, when the pixel sizes are different!

What you need to specify is how big a spot size you need to resolve.

Example 2. You have a camera with 1024 4.65um pixels, and you have another camera with 640 6.5 um pixels. We are going to measure 2 different objects with each camera. On the 1024 camera, the size of the object (your spot size) is 5 pixels across (23um). On the VGA camera, your spot size is 2 pixels across (13um**). Even though you have a megapixel camera with smaller pixels, on the VGA camera your spot size is smaller, so you need a 'better' lens on the VGA (non megapixel) camera!**

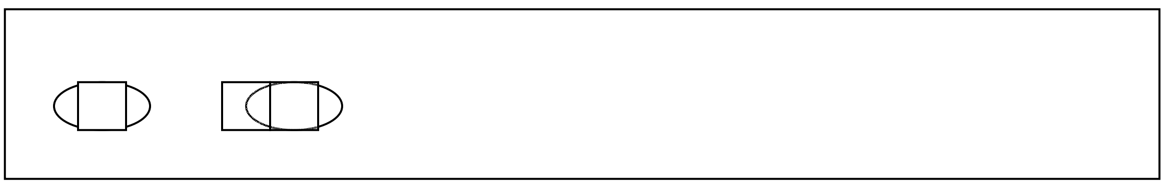
Moral of the story: Find the lp/mm vs. smallest size of object to resolve!

<u>How many pixels do I need?</u>

This depends upon what you are trying to do. Assuming that we have a perfect lens, so it is not limiting the resolution, the more pixels you have, the smaller the object and more accurately you can measure.

If you are trying to just look at large blobs that use a significant % of the sensor (say 50 pixel blobs on a 500 pixel wide sensor), there is obviously no issue.

Now lets say you are trying to measure a blob that is roughly the size of a pixel. To find an edge you need at least 2 pixels. (See simple diagram below, object is oval, pixels are square. To find both edges, we should have 3 pixels)



<u>What about the F# of the lens?</u>

The smaller the F# (f1.2 , f2.0, f2.8 etc.), the larger the iris opening is and that means more light will get through the lens. For each full F stop you close the lens, the amount of light is reduced by a factor of 2. Theoretically, the same F number on two identically sized lenses allows the same amount of light through. In reality, the amount of light that actually gets through the lens is is dependent upon the manufacture of the lens. Coatings on the lenses will reduce the amount of light. How the lens edges are made and the type of lens barrel will determine how much light internal to the lens gets through vs. being absorbed or scattered away. There are still more details beyond the scope of this whitepaper that affect the amount of light coming through the lens.

However, for this article, assume that lens of the same price class with the same F number will allow about the same amount of light through!

<u>What size lens do I need (1/3, ½, or 2/3")?</u>

This is fairly simple. The camera you are choosing, if it is an area scan camera, lists the size of the sensor (this size is a remnant from vidicon tubes, and does not actually correspond to the size of the sensor. In other words, a 2/3" sensor from Sony has a diagonal of 11mm, which mathematically does not work. Do not think you have made an error, it's just the way it is!)

You must use a lens size greater than or equal to the size of the sensor! So for a 1/3" sensor you can use a 1/3", ½", or 2/3" lens, but for a 2/3" sensor, you need to use a 2/3" lens. I should mention that you physically can screw on a smaller lens, but you will see vignetting. This is a fall off in the intensity of light at the corners. It is analogous to looking at something through a paper towel tube. Your field of view is somewhat limited. In some instances, using a larger lens might be advantageous in that the light coming through the center of the lens might have less aberration than the light coming from the edge of the lens. If you have an ideal perfect lens however, there is no reason to use a lens larger than the sensor.

How to compare lenses

If we look at the manufacturers I have listed above, all have similar lenses with similar prices. Lets put them in the following categories, and then compare.

- Security $10 - $70
- Standard Factory Automation (including 'megapixel') $70 - $150
- Multi mega pixel ($200 -$400)
- Really high quality lenses ($500 - $1000)
- Specialty lenses (Telecentrics, short working distance telescopes, long working distance microscopes, zoom, etc.) ($750-$4000)

As always, the old adage applies: **"You usually get what you pay for!"**

My suggestion: Do not compare lenses by the manufacturer's marketing description. Compare by price. The lens market is highly competitive. If brand X is claiming a megapixel lens for $120, and brand Y is the same price but does not call theirs megapixel, they will probably perform the same!

Security Lenses

Lenses for the security market place are normally not as high quality as lenses for the machine vision marketplace. They differ in several ways.

1. They are C and CS. While the world is moving to megapixel sensors, the vast majority of cameras used in security that are already in place are standard NTSC cameras, 640 x 480 interlaced that can connect to TV or VCR devices without a framegrabber. Many of these cameras have CS mounts, and its very easy to turn CS into C, just add a 5mm spacer ring to the front of the camera or the back of the lens. Security also views lots of things in a large FOV, so small focal length, or wide angle lenses are prevalent. Therefore, we see lots of small focal length CS mount lenses.
2. Mostly available in 1/3", and some ½", but moving away from the larger sizes.
3. As security moves to megapixel cameras, lens quality will have to improve, but normally security cameras are not trying to measure single pixel objects.
4. They may not be offered with set screws to lock the iris and focus in place. The assembly line used to monitor metal stamping has lots of vibration; the iris can move. Your local convience store does not have this problem, no matter how hard that 5 year old is stamping his feet at not getting a slushie.
5. The housing might be made of plastic.

6. The lens itself might be made of plastic.
7. It is not intended to be used in a rugged environment.
8. It may not have adjustable iris.
9. Usually do not have front mount filter threads
10. It is less expensive.
11. Costs for fixed focal length 'security' lenses range from about $10 to $70 per lens.
12. Available from all vendors, this is where the real volumes are!

Factory Automation Lenses

"Standard" machine vision lenses cost about $70 to $150 per lens for a fixed focal length lens. They have the following characteristics:

1. All metal housing
2. Lock screws on both the focus and iris to prevent movement from vibration.
3. High quality optics. Some of these lenses are called 'megapixel' lenses. Do not use this definition to evaluate the quality of the lens.
4. C mount. Most industrial cameras have C mount, not CS mount lenses. Note, a C mount lens CANNOT be used with a CS mount camera (unless you want to grind 5mm off the back end)
5. Usually available as 2/3", but some ½" lenses as well.
6. Several vendors try to have all the lenses be as close as possible to the same physical size.
7. Have front mount filter threads on most brands, but some brands try to have the same size mount for as many of their lenses as possible.
8. MTF numbers about 80-100 lp/mm in the center, 60-80 lp/mm on edge. If you can find better numbers than these for this price, it's a good deal!
9. Available from all vendors, but some vendors do not focus on this market as much as security as the volumes are much different, and many of these lenses are 'old' designs. Be careful as some of these designs are 10+ years old, and others are brand new or a few years old at the most. Lens design does not change overnight, but it is certainly different from a decade ago!

Multi megapixel lenses

Multi megapixel lens cost about $200 to $400, and a relatively new class of lens that has been introduced by manufacturers only in the last few years. Some classify the lenses as 5 Megapixels, others as 3 megapixels, however just about all have the following characteristics:

1. All metal housings
2. Lock screws on focus and iris
3. Typically larger in size than the "factory automation' lens, using more glass.
4. C mount and 2/3"
5. Some are available as 1" lenses
6. MTF numbers of 100-120 lp/mm in the center and 80-100 lp/mm at the edges.
7. Front filter mounts
8. Many vendors offer only a few focal lengths. Kudos to those vendors who offer from 5 or 6mm to 75 mm!

Really High Quality Lenses

Available from Schneider Optics, Navitar, and certain Edmund Optics products, these lenses are top of the line lenses. Whereas all the other lenses so far are manufactured for cost considerations, do not have 100% inspection or testing after manufacture and performances varies from lot to lot, these lenses you can always count on to be the same. Further, the optical performance is a grade or more above other classes. Their MTFs do not fall off much at the corners. Finally, many of these lenses are specialty lenses; close focus with high magnification, extremely low aberration, etc.

F Mount Lenses (SLR Lenses)
If you have a sensor that is greater in size than 1" (or about 13mm), a C mount lens might not cover the whole sensor. This causes vignetting. F mount lenses are larger, and will cover larger sensors. You should realize the following about F mount lenses. While they usually are very good optically, they are not designed for harsh environments. C mount factory automation lenses are made for 'dirty' environments. They can withstand shaking and vibration. F mount lenses were designed to fit on your SLR camera and be held in your hand. They usually have plastic bodies, and in an industrial setting will shake apart! Be careful about where you use a F mount lens.

So how do I choose a lens?

1. Have a very small spot size to resolve? Use a higher 'class' of lens. Multi megapixel or more.
2. Using a mega pixel camera? Use a multi megapixel lens if possible. You are spending between $1,500 to $15,000. Why not consider spending an extra $50 to $150 to at least go from the factory automation class to multi megapixel class? It's little extra vs. the cost of the camera, cable, accessories, computer, etc.
3. Using a sub megapixel camera, but have to do precise or repeatable measurements? Again, consider using a multi megapixel lens, or at least , a high quality factory automation lens.

1stVision carries lenses from Computar, Pentax, Kowa, Tamron, Edmundoptics, Rainbow, Fujinon, Navitar, Linos, Schneider, and OEM brands. Some lenses, while they seem the same, really work better or worse in different applications. Unless you have compared these lenses yourself in the lab, please call us to explain your application. We can recommend the best lens for the application and price range! We get calls every day from someone who wants to purchase brand X, but when we ask about the application, we find out that for the same price they can be getting a better lens, or be getting a lower price on the same performance lens!