Lens and Sensor Compatibility

White Paper

May 2017

Author:
Daniel Bates

Scorpion Vision Ltd
+44 (0)1590 679333

Table of Contents

1.0 Introduction

If you are looking to purchase a camera and/or lens for machine vision, you will find that not every lens is compatible with all cameras. This document aims to help you learn how to make sure the lens and camera that you choose will be compatible.

There are many factors that determine the compatibility of a lens and camera. The main factor is the sensor size or format. Cameras come with a range of sensor sizes and lenses are available in equivalent formats. Another factor that affects compatibility is the megapixel rating. In this document we will look at the different sizes and megapixel ratings and discuss how these affect compatibility between different cameras and lenses.

2.0 History of Sensors

2.1 CCD and CMOS

The first digital imaging sensors were charge-coupled device (CCD) sensors. The CCD was invented in 1969 by Boyle and Smith of Bell Labs. The first working CCD was demonstrated in use as a very basic 8-pixel linear imaging device. Development continued to progress very quickly and by 1971 a team were able to capture the first images with simple linear devices. The invention was noticed by several companies and they began to develop it for themselves. In 1973 researcher Gil Amelio lead a team to produce the first commercial CCD. In 1975 a Kodak Electrical Engineer called Steven Sasson created the first digital camera using this CCD.

Most sensors today use the cheaper CMOS (complementary metal-oxide-semiconductor) format and although CMOS sensors have been around for as long as CCDs it was not until 1989 when researchers published a paper that reported work on CMOS image sensing and this culminated in the design and demonstration of the world's first single chip CMOS video camera. CMOS has now (May 2017) almost superseded CCD as it has overtaken the older technology with higher frame rates and resolution. To achieve these high frame rates the camera needs to be paired with a high speed lens. These will have low f-numbers to maximise the light reaching the sensor allowing for more frames per second to be captured.

2.2 Origin of Sensor Sizes

The formats used to describe the size of a sensor (such as 1” and ⅔”) are not descriptive of the physical measurements of the sensor itself. This is because the measurements used for sensor sizes originate from before the invention of digital sensors. These measurements originally related to the diameter of the glass tube used in the first tube cameras used to capture TV images before the introduction of the CCD.

The area of the face of the tube used to create the image was smaller than the outside diameter (usually about ⅔). This means that a 1″ tube would give a 2/3″ diameter active area which would contain a 16mm diagonal frame inside. This means that a modern 1” sensor is a sensor with a 16mm diagonal.

Although this makes little sense in our modern world it does mean that the same 1″ lenses used on tube cameras are compatible with modern 1″ format cameras and will provide the same field of view. Because of this the sizes have remained despite the fact that they have little to do with the physical size of a modern sensor.

3.0 An Overview of Common Lens Types

The type of lens play a large role in sensor and lens compatibility. Not only don’t every lens fit all cameras but the size of the mount often affects the formats that that type of lens is available in.

3.1 M12 or S-Mount Lens

M12 lenses are miniature lenses and further described in this document.

3.2 CS-Mount Lens

CS-Mount lenses are more efficient in cost and size than the standard C-Mount lenses. A CS-Mount lens has a smaller distance between the lens and the sensor allowing for a greater field of view. These lenses can only be mounted on CS-Mount cameras and usually come in smaller formats such as ¼” and ⅓”.

3.3 C-Mount Lens

C-Mount lenses are the most commonly used lens in machine vision due to having manually adjustable iris and focus. They are able to focus in a shorter distance than CS-Mount lenses. This means that you can have longer distance and still achieve a very large field of view. A C-Mount lens can fit on CS-Mount cameras in addition to C-Mount cameras (see below). The most common format for C-Mount lenses is ⅔” but they are also available in ½” and 1” formats.

3.4 Mounting a C-Mount Lens on a CS-Mount Camera

Although a CS-Mount lens cannot be mounted on a C-Mount camera, a C-Mount lens can be mounted on a CS-Mount camera. This is because a CS-Mount lens requires a smaller back focal distance (12.5mm for CS-Mount vs 17.5mm for C-Mount). A C-Mount lens can be increased to the required distance using a 5mm C/CS ring enabling it to focus correctly. Obviously the reverse cannot be achieved due to the physical dimensions of the camera.

3.5 High Speed Lenses

High speed lenses are suitable for cameras that operate at high frame rates. These are available across different mount types. They have low f-numbers which allows the maximum amount of light to reach the sensor and enabling the camera to capture more frames per second.

4.0 Industrial Camera Sensor Sizes

4.1 Comparison of Common Sensor Sizes

Industrial camera sensors come in a range of sizes. The diagram below shows the most common sensor sizes used for machine vision to scale.

4.2 Sensor Sizes Millimetre (mm) Equivalents

As discussed earlier the format of a sensor is not representative of the physical size of a modern sensor. Sometimes for certain applications it can be useful to know the physical dimensions of a sensor in mm. Below are the equivalent dimensions in mm for each of the common sensor formats.

Sensor Format	Dimensions (mm)		
	Diagonal	Width	Height
1/4"	4.5	3.6	2.7
1/3.2"	5.7	4.54	3.42
1/3"	6	4.8	3.6
1/2.5"	7.2	5.76	4.29
1/2.3"	7.7	6.16	4.62
1/2"	8	6.4	4.8
1/1.8"	9	7.18	5.32
2/3"	11	8.8	6.6
1"	16	12.8	9.6

5.0 How Sensor Size Affects Compatibility

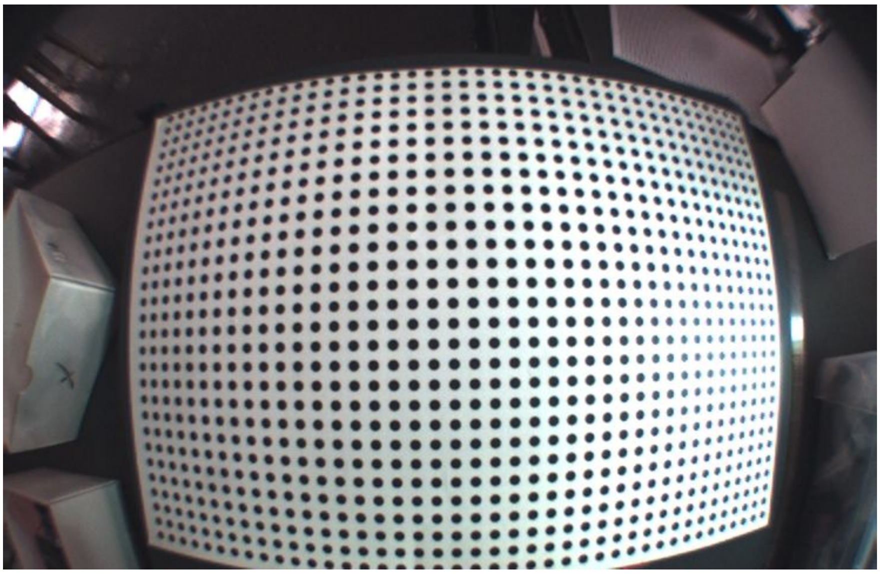
As already discussed industrial cameras come with a range of different sensor sizes. To ensure that lenses are compatible they are designed for use with different size sensors. The format of the lens will be listed in the specifications and follow the same convention as sensor sizes. This applies to all lens mounts including M12 (S-Mount) and C and CS-Mount as well as F-Mount lenses which are used with line scan cameras but most commonly are used with consumer SLRs.

For the best results cameras should be fitted with the corresponding lens. For example using a ⅔” lens with a ⅔” camera. Although this delivers the greatest chance of compatibility it does not mean that non-matching camera and lens combinations cannot be used but issues may be encountered as seen below.

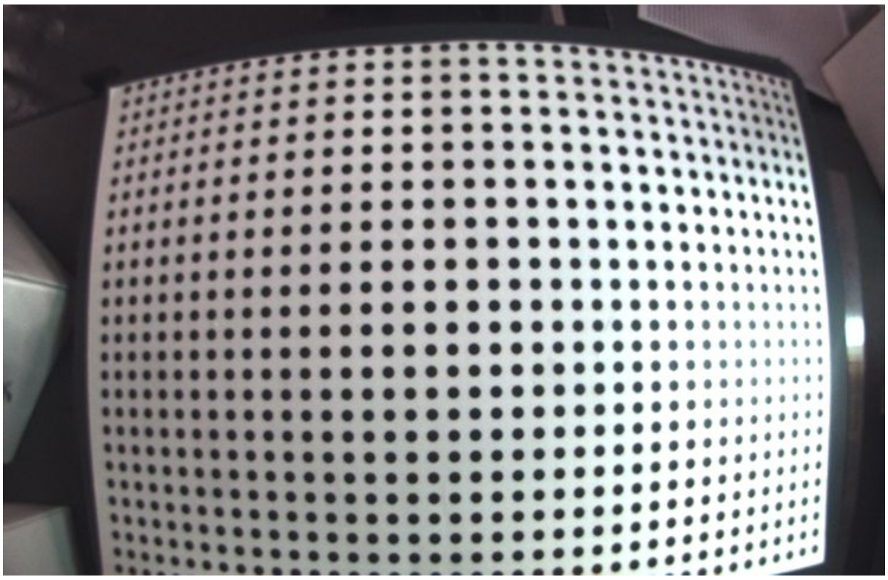
5.1 Example Images

One of the most common formats for small industrial cameras is a ⅓” sensor . Here we have used the DFK 22AUC03-F (Aptina MT9V024 sensor) with M12 lenses of various formats.

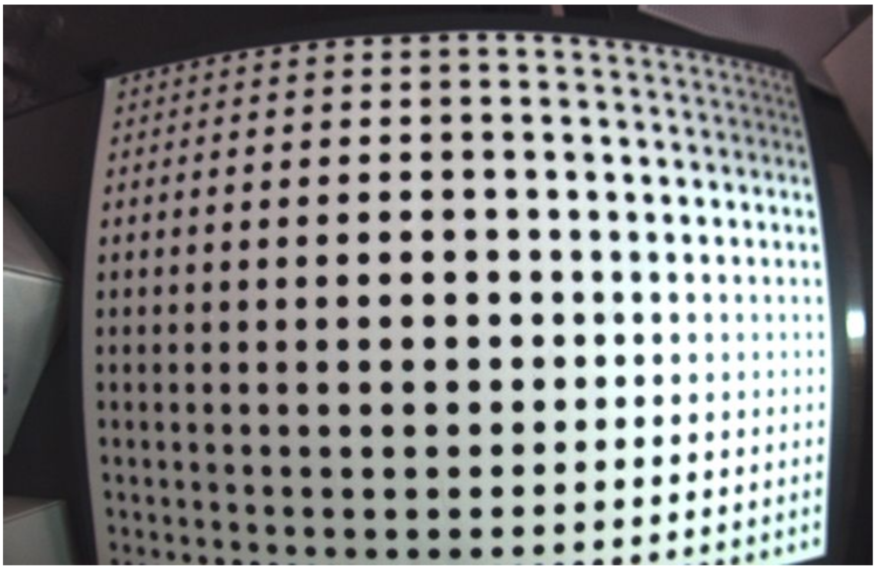
First up we used a ¼” format 2.2mm lens. In this situation the lens is smaller than the sensor which creates a compatibility issue. Vignetting occurs because the lens itself is blocking the sensor. This is seen worst in the top corners of this image. In this case the effect is minor but increasing the difference in format between lens and sensor will worsen the vignetting.



Next we used a 1/2.7” format 2.4mm lens. Because this lens is larger than the sensor there is no vignetting of the image. This means that images captured in this combination are perfectly usable. The issue with incompatibility in this situation is what is known as “crop factor”. The sensor is not able to capture all of the image coming through the lens and therefore some of the image is lost. This means that the captured angle of view will be less than stated in the specification. Using a larger sensor with a format matching the lens would enable the whole image to be captured and maximise the field of view.

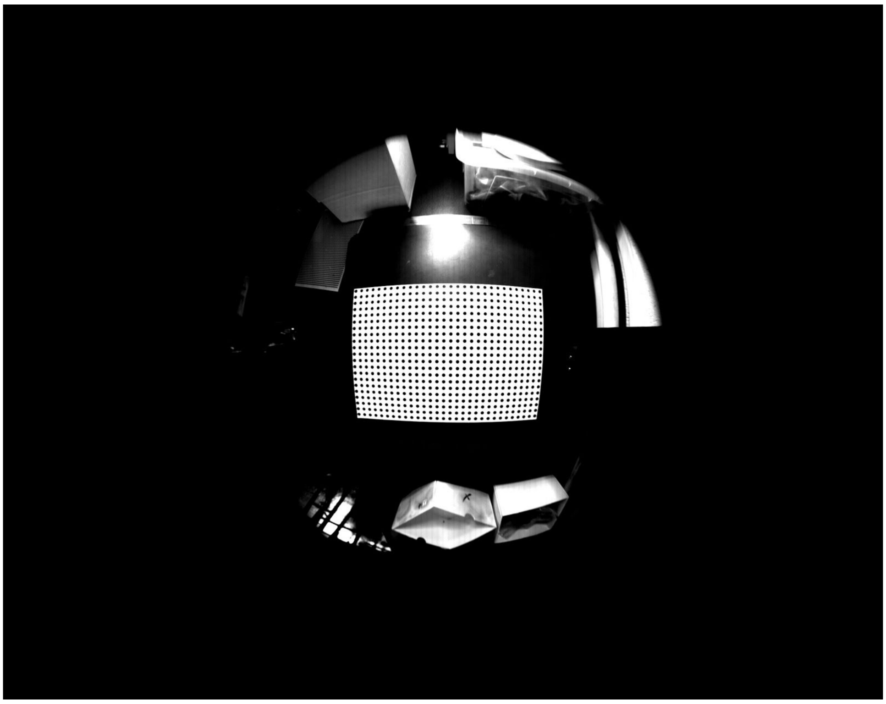


Finally we used a ⅓” format 2.5mm lens. This lens format matches the sensor size and therefore it has maximum compatibility with the camera. There is no vignetting shown and the field of view will be at the maximum possible for the lens.



The maximum sensor size for industrial cameras is usually 1”. We used the PL-D725MU (OnSemi Vita5000 sensor) with some different lenses.

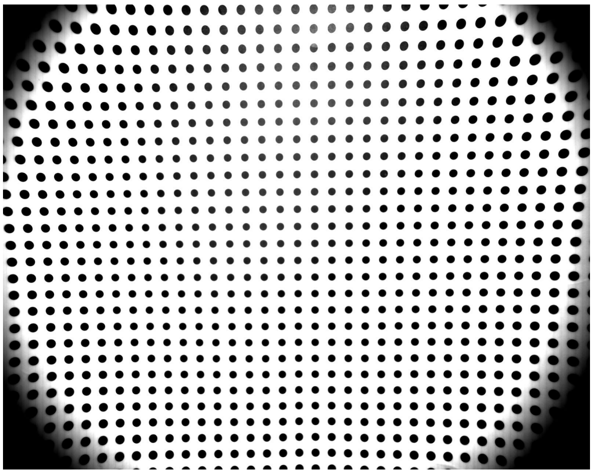
First we used a ⅓” format 2.5mm M12 lens. This combination exaggerates the issue when a small lens is used on a large sensor. This image clearly shows the aperture of the lens and highlights the most extreme example of incompatibility between lens and sensor.

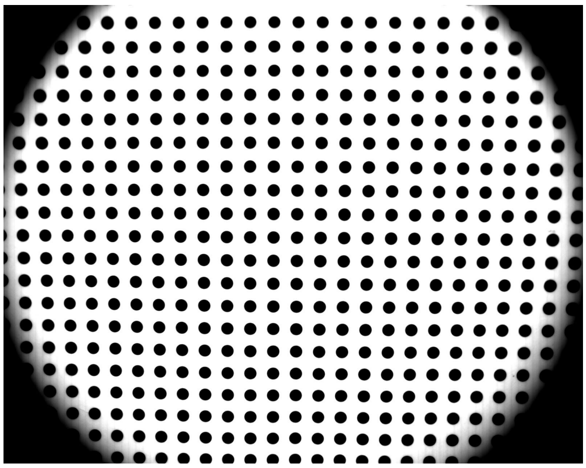


Next up we used an 8mm 1/1.8” format C-Mount lens and a 12mm ⅔” format C-Mount lens.

These images show (to a lesser extent) the vignetting seen above.

A 1” lens would be needed for complete compatibility but these are reasonably rare and expensive therefore could not be sourced for testing purposes.





6.0 How Megapixel Rating Affects Compatibility

Most people are familiar with megapixel ratings on digital cameras but when it comes to industrial cameras, lenses and cameras have their own megapixel ratings. For maximum compatibility the rating of the camera used should match that of the attached lens.
In the past the resolution of a lens was almost irrelevant due to the low resolution of the camera itself. Nowadays industrial cameras can range from VGA (0.3MP) up to a massive 42MP meaning higher resolution lenses are needed.

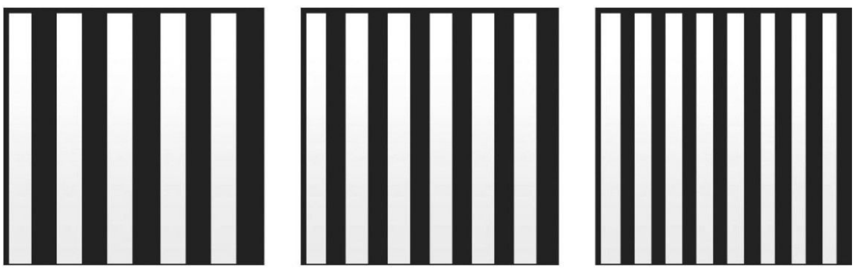
The official measurement of lens resolution is in line pairs per millimetre (lp/mm). The lp/mm of a sensor may be given in the camera specifications or can be calculated using the megapixel rating and area of the sensor but this is complex. Fortunately to make things simpler most manufacturers will provide an equivalent megapixel rating for lenses to make it easy to match to compatible cameras. Scorpion Vision offers M12 lenses with ratings from 1MP to 10MP and C-Mount lenses from 1MP to 5MP.

The quality of an image taken using a high megapixel rated camera will be limited by the attached lens. A lower resolution lens will reduce the image quality from a high megapixel camera. The reverse is also true as a high resolution lens will not provide the stated resolution if attached to a camera with a lower megapixel rating.

6.1 Lens Quality

Although megapixel rating can be used to gauge compatibility and for basic comparisons between lenses it is only an estimate of lens quality. Professional imaging specialists use MTF (Modulation Transfer Function) to measure the performance of optical systems. This area of optics is very complex and can only be fully understood by experts with a deep background knowledge on the subject but a basic overview can assist in understanding lens and sensor compatibility.

A variation of MTF is used in the humble eye test.
The MTF is a function that represents both the resolution/frequency and the contrast/modulation of a lens. To calculate both these components a test chart of black and white bars (see below) is used to calculate the maximum lp/mm (resolution) and the distinction between the black and white (contrast).



Resolution and contrast data is plotted on a graph to create an MTF curve for visual comparison of lenses. These graphs can be read to determine the optimum combination of components although for most people they are too complex to understand.
All of the components in a system (including lens, sensor and cables) have their own MTF and these can be combined to calculate the overall MTF of the system.

7.0 Summary

- A large sensor size cannot be used with a lens that is designed for a smaller sensor, ie. you cannot use a 1/3” format lens with a 1/2” sensor as this causes vignetting.
- A large format lens CAN be used with a small sensor. ie. a 1/2” format lens CAN be used on a 1/3” sensor although field of view will be reduced.
- A ‘High Speed’ lens should be used with a high frame rate, or in low light conditions.
- The megapixel rating of a lens should match that of the attached camera to achieve maximum image quality.
- ‘MTF’ is a measurement of the quality of an optical system and the technique used is similar to that of an eye test