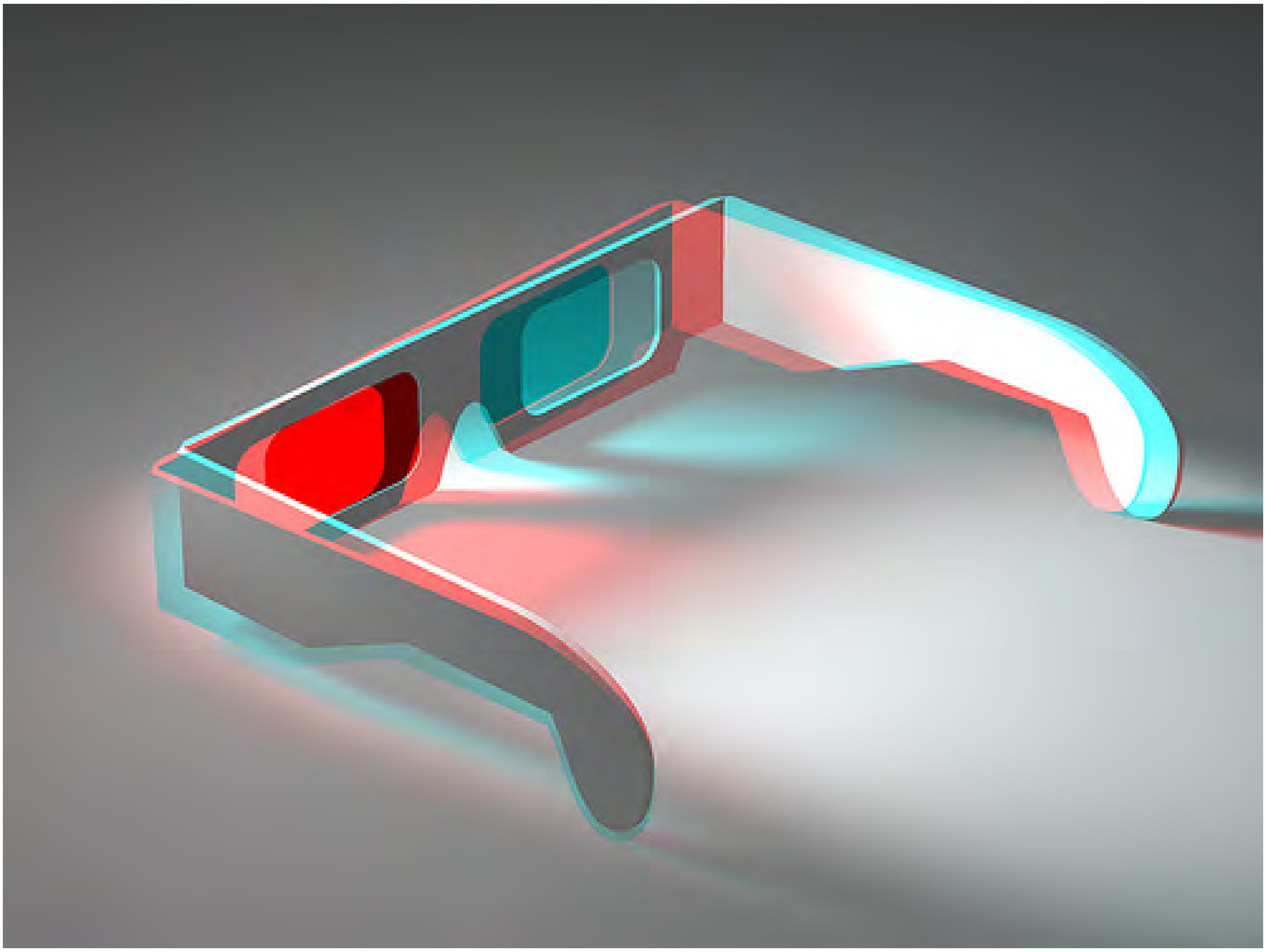
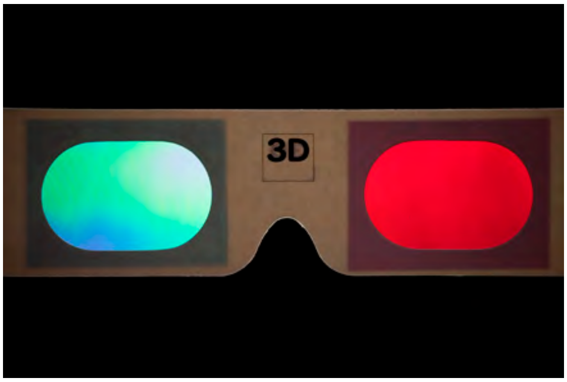
CAMERA REQUIREMENTS FOR 3D METROLOGY



Adimec

As the objects to inspect/measure in high-tech manufacturing become smaller, higher-resolution cameras with better spatial resolution can improve accuracy and precision. This requires a high-quality machine vision camera design, or what is now called a metrology camera. 3D measurements in particular pose increasing demands on camera performance and reliability. This paper discusses critical parameters, depending upon the specific measurement technique.



Nowadays the ever increasing demand for smartphones and tablets requires state-of-the-art production with high-speed inspection for high yield. These devices require smaller and more complex printed circuit boards (PCBs) and electronic components, resulting in a need for more accurate manufacturing and measurements. This happens on an aggressive time scale as consumer expectations for new improvements result in fast innovation cycles. Not surprisingly it is driving innovations in supporting products, including machine vision.

High-resolution cameras combined with high speeds that make full use of select image sensors provide the images required for inspection and metrology of the latest generation devices. This includes supporting the move from 2D to 3D measurements.

In addition to resolution and frame speed, there are other camera parameters to consider for accurate 3D metrology. A few applications will be described in detail to demonstrate how to determine the most important camera parameters for specific applications.

MACHINE VISION CAMERA PARAMETERS

Several machine vision camera parameters must be included when analyzing the fit of a camera within an automation system:

» Resolution (horizontal x vertical pixels)
  Today 4 to 25 Megapixel cameras are common. Higher resolution allows for larger inspection areas and/or higher accuracy.
» Pixel size
  Whereas consumer cameras have pixels that are less than 1um in size, machine vision cameras typically have pixel sizes ranging from 4 to 10um. Smaller pixels may result in cheaper cameras at the cost of poorer measurement accuracy.
» Frame speed
  System speed is one of the most important selling points for in-line equipment manufacturers; this is directly achieved by increasing frame speed.
» Digital interface
  The digital interface chosen greatly influences the system design as it determines cable length, flexibility, and overall system costs.
» Functionality and software support
  This is important during the design phase, but it also influences maintenance costs during the lifetime of the equipment.
» Spectral response
  The image sensor's spectral response has to match the spectral response of the light source used. A poor match between illuminator wavelength and sensor quantum efficiency (Qe) results in poor measurement accuracy due to too much noise in the image, or leads to the selection of a more expensive light source.
» Read noise
  This determines the noise floor in dark image areas and influences the accuracy of the measurement.
» Full well capacity
  This determines the noise in bright areas of the image and influences the accuracy of the measurement.

- Photo response linearity
  Most measurement methods assume a linear response of the pixel to light but this may not be true from raw image sensor output.
- Image non-uniformities
  Dark signal non-uniformity (DSNU), photo response non-uniformity (PRNU), striping, shading, and defective pixels, columns and rows all influence measurement accuracy.
- Modular transfer function (MTF)
  The MTF determines how "sharp" the image is and determines the smallest errors that can be detected and the measurement accuracy. Note that the MTF of an image sensor is wavelength-dependent and in general deteriorates at longer wavelengths (such as near-infrared light).

Not all of these parameters can be optimized at the same time and the most important specifications depend on the application. The increasing trend from 2D measurements to 3D results in more stringent requirements for the camera. This makes it even more important to prioritize the key specifications to avoid unnecessary costs. There are several measurement methods commonly used in semiconductor and electronics manufacturing, which provide good examples of this.

Figure 1 shows three often used 3D measurement methods, each with a different measurement range and accuracy level: laser triangulation, fringe projection, and interferometry.

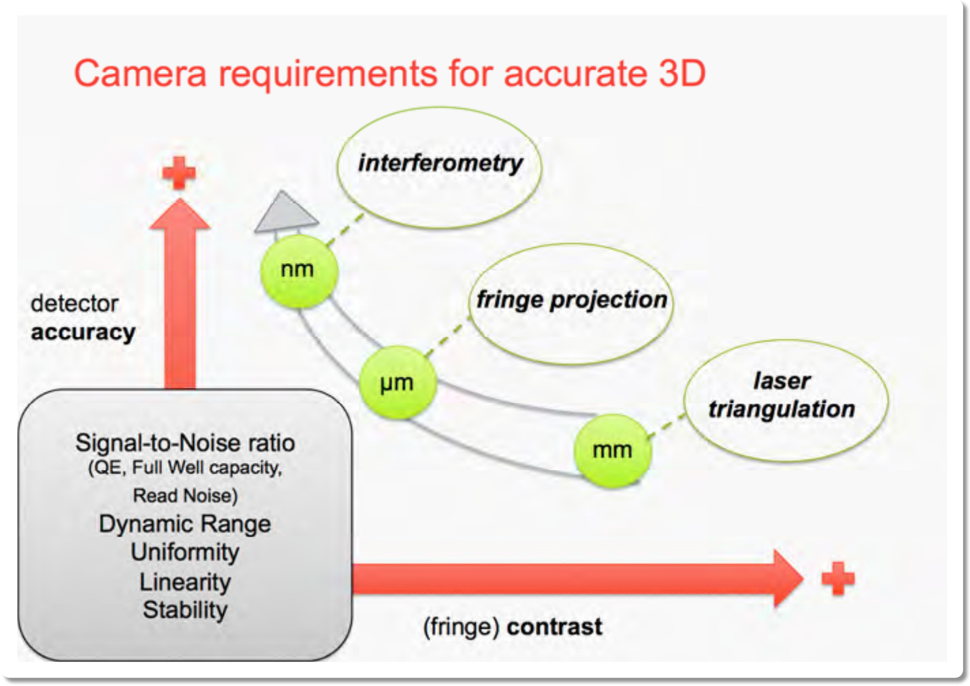
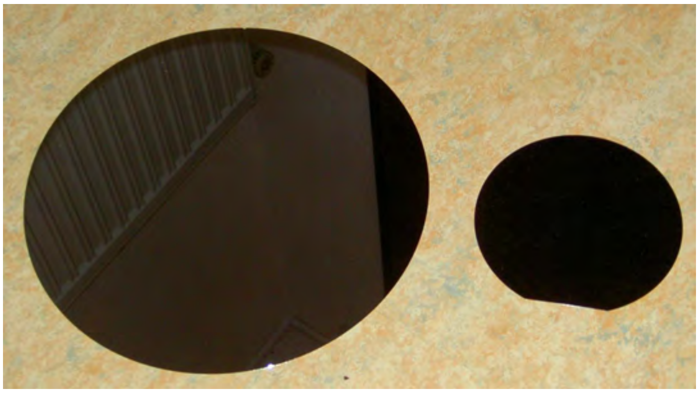


Figure 1. Overview of camera requirements for accurate 3D measurements, depending on method used

The "simplest" method is laser or LED triangulation. We will not delve deeper into this method since it is considered a mainstream application in machine vision and can usually be achieved with standard cameras as they exist today, even for 3D measurements. When increased accuracy is needed in the micrometer and nanometer range, optical measurement methods such as fringe projection and interferometry are used. The following sections describe these methods in more detail.

SEMICONDUCTOR WAFER THICKNESS AND FLATNESS MEASUREMENTS



(Source: Wikipedia)

Before any transistor is laid down, the incoming silicon wafer must be analyzed for flatness and defects. From this inspection, wafers can be classified to allow for the best wafers to be used for the smaller technology nodes. Typically measurement techniques such as interferometry are used.

Fringe projection is a lighting method that projects a striped pattern with a certain period (i.e. distance between black/white) onto a surface to support phase shift measurements. By moving the pattern over the surface, you can calculate a phase shift out of multiple images. Phase shift measurements can also be obtained via interferometry. With fringe projection you can measure in the micrometer scale and with interferometry in the nanometer scale.

This technique works because when two waves with the same frequency combine, the resulting pattern is determined by the phase difference between the two waves.

Waves that are in phase will undergo constructive interference and waves that are out of phase will undergo destructive interference (see Figure 2). In practice, the light beams will have different intensities, so the result will not be true 200% - 0%.

Interferometry measurements would be very difficult and expensive if the entire full-size wafer (300 mm) were imaged in one view. The optics costs alone would be exorbitant. Therefore, typical interferometry methods (i.e. Mirau or Fizeau, see Figure 3) use small-size optics to perform many accurate measurements that are stitched together into one flatness map (see Figure 4)

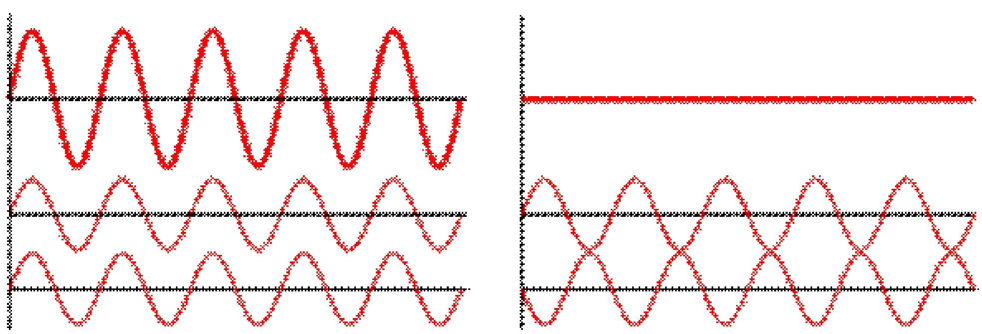


Figure 2. Interference of two waves, with the results depending on their phase difference (Source: Wikipedia)

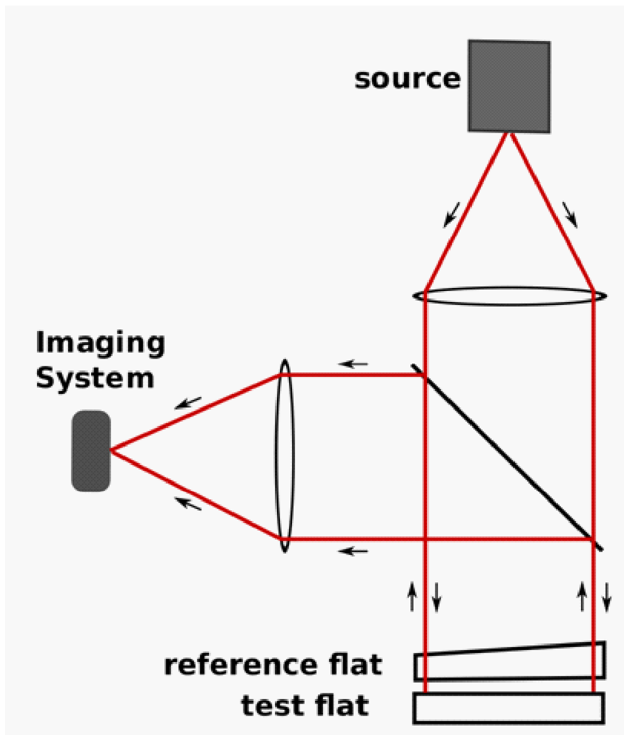


Figure 3. Fizeau Interferometry set-up (Source: Wikipedia)

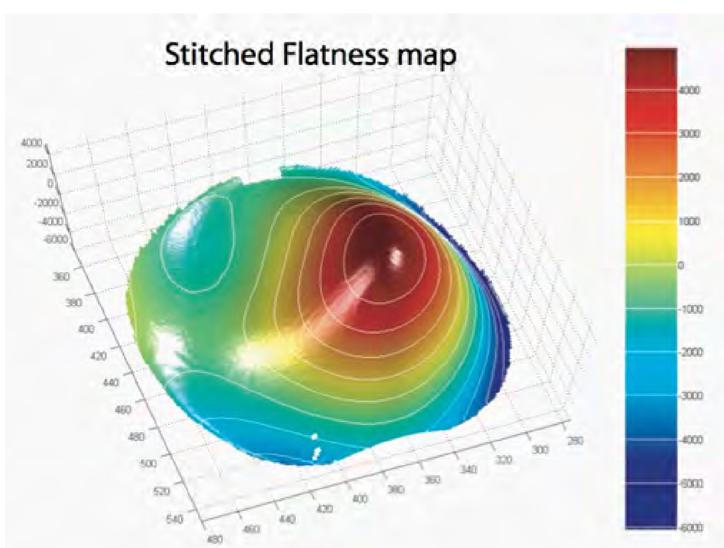


Figure 4. Combined wafer flatness map (Source: Eindhoven University of Technology)

In order to then prioritize the camera requirements for this application it is helpful to first think of the image or images required for the measurement. For interferometry, several images are required, information in the entire image is used, and there is limited contrast in the images.

Therefore, the most important camera specifications to consider are:

- Dynamic range to provide detailed information in low contrast images
- Image uniformity for accurate data over the entire image
- Full well capacity since shot noise is the dominant noise source
- Frame rate to not limit throughput since many images are necessary for one measurement
- Image-to-image stability because multiple images are combined for the measurement
- Mechanical / Thermal stability to support image-to-image stability

Image sensor optimization, precise sensor alignment and specialized verification procedures are all measures that would be taken with metrology cameras, but may not be done with most mainstream cameras.

Metrology cameras are specially designed to ensure the best pixel data. With a full understanding of the image sensor, there are ways to drive the sensor in a specific way for an application to increase performance. For example, by tuning the sensor to certain settings, camera manufacturers can reduce the amount of defects the sensor generates. Defects and non-uniformity generation depends not only on the sensor design but also on the conditions in which it operates, like temperature. Camera embedded calibrations can also be done automatically in the field to adjust to system conditions, such as temperature variations, optics imperfections, and clocking. These measures among others provide the dynamic range, full well capacity, uniformity, linearity, etc. necessary for detection of small changes and accurate measurements.

Uniformity challenges increase as a larger optical field-of-view requires more complex optics and with the increase of defect pixels in the sensor. Camera manufacturers can provide higher uniformity by grading the incoming sensor, including dedicated processing and eliminating blemishes in the manufacturing process and camera operation as mentioned before.

While higher frame rates allow for gain in throughput, the image sensor design must be able to handle these high data rates within a critical timing tolerance to reliably produce quality images. The resulting camera must ensure that the frame rates are actually captured in a consistent and dependable way. A reliable high-speed camera interface ensures no loss of data when the images are transferred to the system.

Variations in the image should be smaller than the variations one is trying to measure! With both consistent images and camera-to-camera consistency (when multiple cameras are used per measurement or multiple tools are used per process line), any changes detected can be determined as process deviations, allowing root cause analysis to take corrective action.

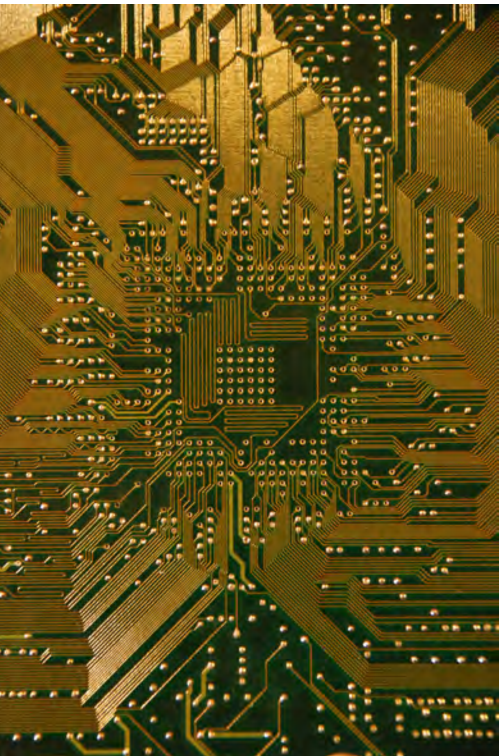
Image-to-image consistency is maintained through a robust camera design as well as embedded functions. Camera-to-camera consistency is achieved through detailed sensor mounting and alignment processes as well as rigorous, individualized assembly and test procedure process so that mechanical and electrical adjustments can be made and tight tolerances met.

PCB INSPECTION

When the integrated circuit is completed, there are several inspection steps in the packaging process and subsequent PCB manufacturing. Increasing performance while reducing size results in smaller chips, different packages, higher-density PCBs, and multi-layered, more complex boards. There are also a large variety of component sizes.

For years 2D was dominant and the third dimension with limited accuracy was only used occasionally. With feature sizes continuously decreasing and new packages being introduced (e.g. BGA, flip chip), the third dimension became more important and made improved measurement methods necessary. Modern systems use advanced lighting techniques and algorithms to perform true 3D measurements with high accuracy.

With solder paste inspection, 3D inspection and measurement is also becoming more important because of the changes in the amount of solder paste used. When the solder bumps and balls become smaller, the volume of the solder paste is the important measurement factor and not just the width. As the solder provides the connection with the PCB, the correct solder volume is extremely important to achieve a higher solder joint reliability. Solder volume and shape are measured both pre-reflow and post-reflow of the solder.



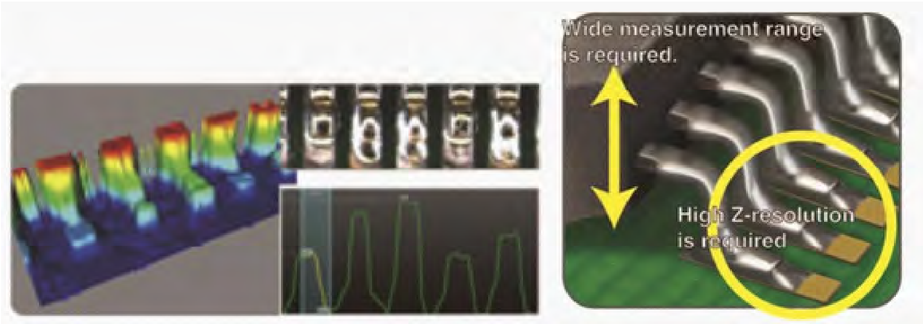


Figure 5. 3D Automated Optical Inspection

A common technique used in electronics manufacturing is 3D Optical Inspection (AOI), which offers significant improvements over 2D, such as full dimensional measurements to verify the exact component information, see Figure 5.

For example, high-speed 3D AOI systems that employ fringe pattern projection (triangulation, multiple directions, multiple colors) need more megapixels to measure the third dimension. With just a 2D view from the top, you can only see defect such as shifts, rotations, and cracks but not whether components are flat on the board or the volume of solder paste. With 3D, only one image was sufficient to get all of the measurements.

While some 3D measurement systems may use four to five images per inspected region of interest (ROI), more advanced systems use twenty images or even more to increase measurement accuracy and to add color vision.

The migration from one image for measurement to multiple images results in more demands on the camera-based imaging systems. There can be two approaches to satisfy these requirements. The first is to go to a higher resolution camera, which we will discuss in more detail below.

Another option to efficiently capture multiple images is through multiple cameras. This can mean fewer illuminators and less stringent requirement on the speeds of the camera.

This is attractive because it allows for scalability using more low cost cameras for higher end systems. This should be done with caution, though, as the cameras can have lower frame speed, but need to be extremely consistent and well-matched for this technique to be effective.

So with 3D AOI, the most critical camera parameters are:

- Frame speed to maintain or increase throughput
- High resolution to increase the field of view (FOV)
- Qe and read noise as increasing illumination power is expensive
- Uniformity since with higher resolution there can be more defective pixels in the sensor
- Image-to-image stability, as the measurement uses many consecutive images
- MTF, which determines the smallest details that can be seen

Higher resolution cameras allow for a larger area to be inspected at once and provide more data, which can improve accuracy. But since many images are required to perform quantitative measurements and the overall system throughput must be maintained, the camera frame rate must also be high.

Previously 3D measurements could not take advantage of high-resolution cameras because the frame rates of very high-resolution CCD image sensors were far too slow to keep up with the throughput requirements of inline measurement systems, such as 3 fps for 16 Megapixels. Now there are several new high-resolution cameras available using CMOS image sensors that can produce CCD-like image quality at impressive frame rates, such as 25 Megapixels at 32 fps (or with the ROI function, 16 Megapixels at 45 fps, for example) or 12 Megapixels at 180 fps.

For high accuracy and precision, particular care must also be given to the optical design and precision of the image sensor placement, especially with high-resolution. If there is any tilt in the mounting and positioning of the sensor, one edge of the image could be sharp while the other edge is blurry, making part of the image unusable. The alignment of the image sensor is key in order to have an optimal optical path and high-quality image data for the entire resolution. This can mean fewer illuminators and a less stringent requirement on the speeds of the camera.

With more than 25 million pixels or even 1 million pixels on an image sensor, not every single pixel can perform perfectly. By grading the incoming sensor, dedicated processing and blemish elimination in the camera manufacturing process and camera operation, high-resolution images with high uniformity can be achieved. The necessary image quality over the full resolution must also be maintained at the high frame rates as mentioned before. Careful image sensor selection and tuning can maximize the Qe and read noise for the wavelength of interest.

Since multiple images are combined, the stability and reproducibility in the camera is more critical than in the past. Only intentional changes can occur between the images.
For instance, black level and gain must be exactly the same for all of the images. These parameters are all controlled through the camera manufacturer's design and implementation.

Some additional notes on MTF: MTF is widely accepted as an important factor with lens selection. It is often not considered with the sensor/camera selection. MTF provides an indication of the sharpness of the image or image quality and is determined by both the lens and the sensor.

Lower MTF limits the resolution of the system. As a result, small details of objects are no longer discernable. This is wavelength dependent. In some cases, this can be overcome to some extent by decreasing the noise level, which does cause a reduction in contrast, by increasing the light level.

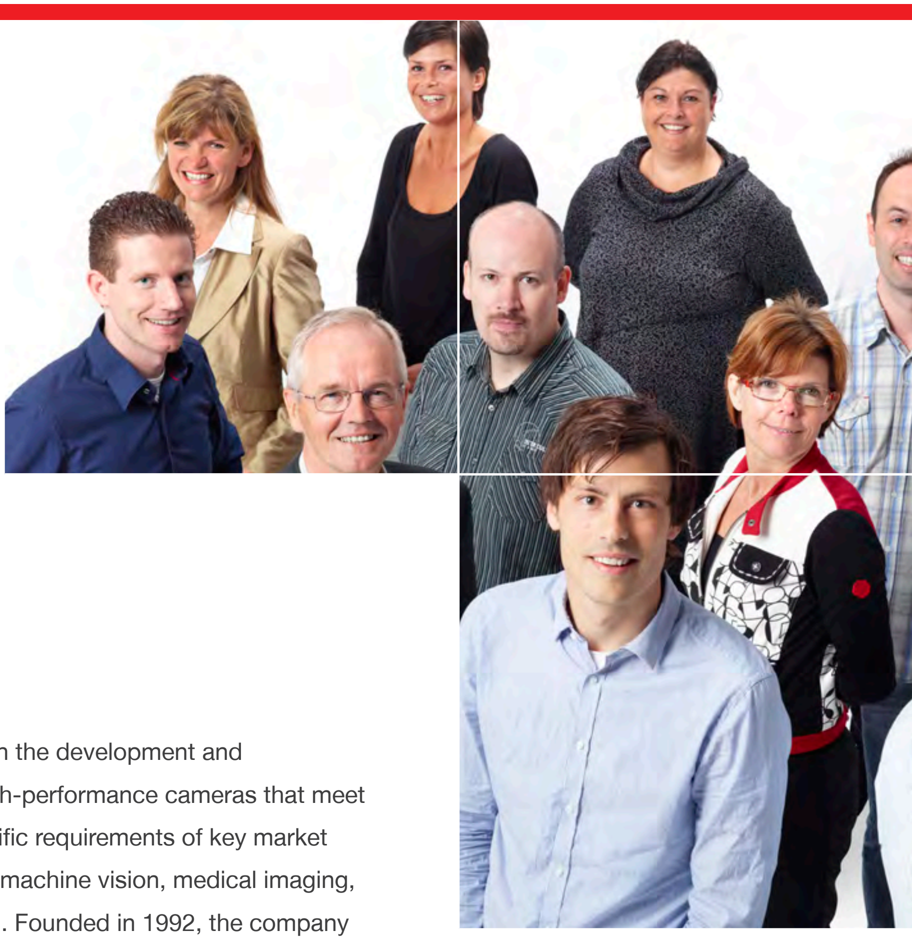
Experienced camera manufacturers will have measured the MTF of the implemented sensor for the full wavelength range and can make the appropriate recommendations for your application.

CONCLUSION

As objects to inspect/measure become smaller, higher-resolution cameras with better spatial resolution can improve accuracy and precision.

An efficient camera design and manufacturing process for defect pixel and blemish correction, accurate sensor alignment, and sensor tuning maximize the most important parameters for measurement accuracy. These extra measures are taken with metrology cameras.

Regardless of the specific implementation, 3D measurements mean increasing demands on the operation and reliability of the camera. By considering the particular needs of an application and measurement method, the most critical metrology camera parameters can be revealed for the best system fit and the performance leap required.



ADIMEC

Adimec specializes in the development and manufacturing of high-performance cameras that meet the application-specific requirements of key market segments, including machine vision, medical imaging, and outdoor imaging. Founded in 1992, the company partners with major OEMs around the world to facilitate the creation of industry-leading cameras.

The unique Adimec True Accurate Imaging® technology provides new levels of precision and accuracy to vision systems. Its diverse line of camera products meet a wide range of performance, size, cost, interface and application requirements. Adimec has offices around the world focused on creating customer value and satisfaction through local, personalized support.

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