Metrology

White Paper

Introduction to metrology

Metrology is the science of measurement. Dimensional measurement is an essential step in components manufacturing in order to ensure that each workpiece meets the required tolerances. Although this task was accomplished in the past by means of contact measurement devices (calipers, micrometers etc.), the growing demand for speed and efficiency has shifted the attention of the industry to optical metrology, which eventually became one of the most important branches of modern machine vision.

Compared to manual inspection, a machine vision system has many advantages: accuracy, consistency and speed are all increased, 24/7. Of course, the best system is the one where the right components have been carefully chosen for the specific task. Hence, let's start diving into metrology by discussing the essential vision components and how to choose them properly.

What to expect from this document

This document is dedicated to machine vision engineers and automation experts who want a quick introduction to the world of machine vision metrology. This is a very interesting and wide topic that would require a much longer discussion... that's why we can't wait for you to contact us to find out more!

Hardware

In order to provide the best image for a metrology application, we have to select three main components: a lens, an illuminator and a camera. Telecentric lenses are always the best choice in metrology. Their special design creates an image where size is independent of the lens-to-object distance - this is the opposite of standard lenses, where the farther the object is, the smaller it appears. Using a telecentric lens with good calibration software provides incredibly consistent results even when the features of interest are not laying exactly on the same plane, or when the object cannot be perfectly aligned to the lens. High magnification macro lenses are also an option for very small field of view metrology applications, since in that case, the lens depth of field is so small that measuring non-planar features would be nearly impossible.

Illumination is also important: the best choice, when possible, is a backlight, especially a collimated light (see the “tips and tricks” box in the next page). Backlighting enhances contrast on the object edges, which are what we typically use as a reference for measurements. The best option in terms of light color is usually green. Most lenses are achromatic, meaning they are optimized to perform the same across the entire visible spectrum. However, for high-end applications the benefit of using green light (monochromatic at the center of the spectrum) instead of white light (broadband) is clear, since a lens designed to perform well in the blue to red range will deliver its best performance right in the middle (green). On the other hand, front illumination is sometimes needed to measure a part: in that case, we need to enhance contrast without creating shadows which would misrepresent the actual edges we need to detect.

Finally, the choice of the right camera depends on many parameters. Some are not strictly connected to the measurement performance (e.g. camera interface, etc.) while other are critical to the process (e.g. camera resolution, pixel size) since they are related to the physical limits we have to consider in a metrology application (see the “tech corner” in the next pages to learn more about the importance of the right pixel size). Another immediate factor influencing resolution is the choice of color cameras instead of monochrome: the typical color rendering technology (Bayer filter) on a color sensor is in fact the main cause for the loss of resolution compared to monochrome sensors with the same number of pixels.

Software

Software is another essential ingredient in metrology. On one hand, it should never precede the hardware selection, since a bad choice of hardware cannot be fixed with software On the other hand, good calibration and stable edge detection algorithms are necessary to achieve consistent results.

Metrology software must take care of the following:

• **Image distortion**: the image will always have an amount of optical distortion which, if not corrected with the aid of a calibration target during the setup phase, will result in significant variations of the measurement readings across the Field of View.

• **Edge detection algorithms**: most of the time, a measurement is carried out by computing the location of the object’s edges on the image. This can be done in many different ways and not all of them are equal or offer the same efficiency and stability.

Measuring in all the fields

In the previous section we discussed why telecentric lenses are so important - now let's dive a bit into some of the many cases (connected to metrology or not) where these lenses can become our best allies.

MECHANICAL APPLICATIONS

The most common application of telecentric lenses is the measurement of precision mechanical parts. Many of them are components for the automotive industry, such as shafts, valves, pistons and other parts of the engine. Parts like tubes or extruded aluminum profiles are typically controlled off-line by dedicated machines. Telecentric lenses are frequently used to control the dimensions of smaller mechanical parts like:

SPRINGS • SCREWS • NUTS • WASHERS

Milling or turning machine tools need to be measured by specific gauging devices, called "tool presetters", which make wide use of small telecentric lenses and collimated sources.

PLASTIC PARTS MEASUREMENTS

Another typical application of telecentric lenses is measuring rubber sealings, o-rings and plastic caps which definitely need non-contact optical measurement techniques as they are difficult to handle without causing deformations, to their original shape.

GLASS AND PHARMACEUTICAL PARTS MEASUREMENT

Many pharmaceutical glass containers like carpules, vials and capsules are typically measured using telecentric optics to check for seal integrity and detect potential damages (e.g. cracks, chipped rims) in the container. Some relevant applications can also be found in the beverage industry, for instance thread measurement of a glass bottle neck. Syringes as well as many other passive medical components also benefit from telecentric inspection techniques.

ELECTRONIC COMPONENTS MEAUREMENT

Electronics connectors, which are often made of metal parts surrounded by moulded plastics, need to be controlled to assure that they are manufactured according to certain tolerances and that the male and female connectors will fit together. Many other components (like resistors, transistors and integrated circuits) need to be inspected by small telecentric optics to check their integrity, critical dimensions and position and bending of the connection pins. Electronic boards are very often controlled to ensure proper distance between surface mount components.
Solar cells are also controlled in transmission with Near Infrared Telecentric lenses to ensure their integrity. Silicon wafers and LCDs displays are often inspected with telecentric optics.

SPECIAL APPLICATIONS

Other applications include:

- **particle measurement**
- **high precision colour measurement of prints**
- **photolithography mask measurement**
- **filter control**
- **blood analysis and cell counting**

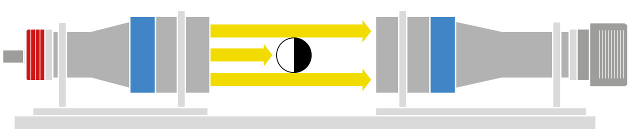
Tips and Tricks

When measuring features on glass, plastic or transparent samples in general, a collimated backlight matched with a telecentric lens is essential to obtain sharp edges. The peculiar trajectory of the light rays, in fact, allows only non-scattered light to reach the sensor, thus creating the perfect silhouette shown in the picture on the right.

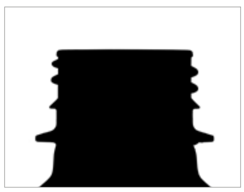
Non-collimated back illumination

Light coming from a variety of angles

Collimated back illumination



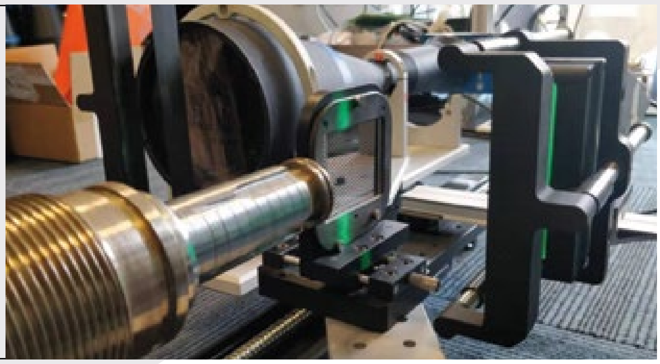
Parallel rays



Application case #1 line scan setup for the measurement of a motor rod

APPLICATION

The task was to measure the width and length of the tip of a motor rod. The region to be inspected is 300 mm in length and 90 mm in diameter (maximum diameter). The application required an accuracy of 50 um or better.



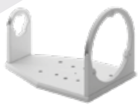
SETUP

TC16M096
Telecentric lens for 35 mm detectors, magnification 0.380 x, F-mount

COE8KLSMCL
Camera CMOS, Camera Link, 8192 x 1, monochrome, 77klps

CMPH064-096
Pattern holder

LTCL4K090-GZ
Telecentric illuminator for linescan cameras, line width 90 mm, green



CMHO096
Clamping mechanics for TCxx085, TCxx096 lenses and LTCLHP096-X illuminators

SOFTWARE

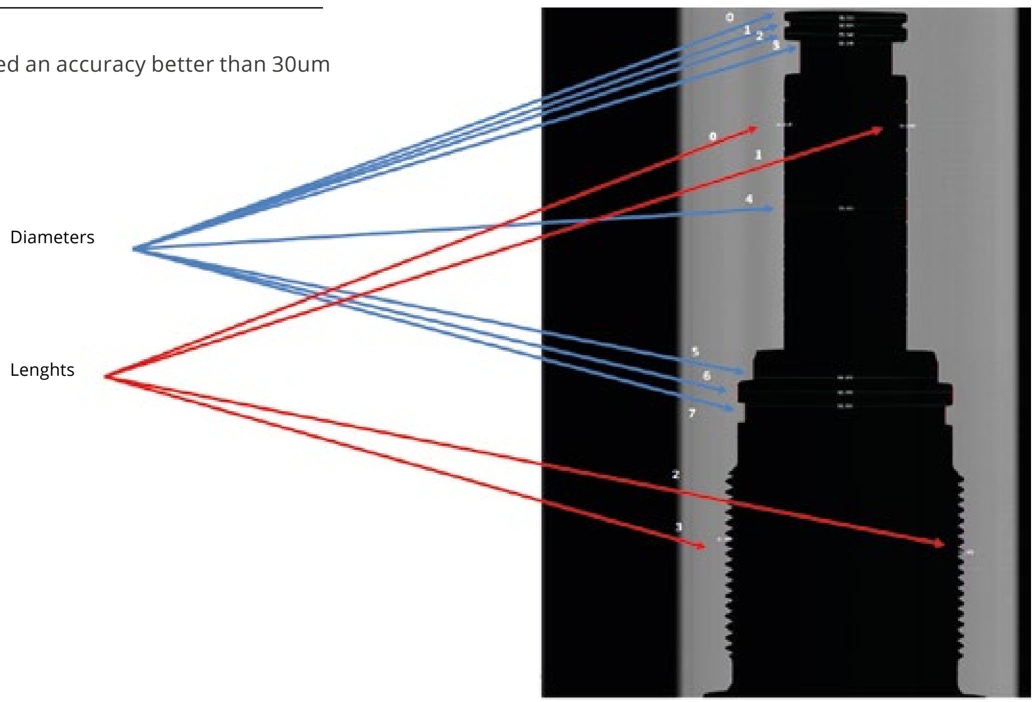
Images were processed with FabImage Studio Professional, a data-flow based software by Opto Engineering® specifically designed for machine vision engineers.

MEASUREMENTS

The line scan vision system imaged the part across its length, measuring 8 diameters parallel to the linear sensor and 4 threads perpendicular to it. This also served as an index for the good alignment and repeatability of the system itself.

RESULTS

All of the measurements achieved an accuracy better than 30um on a 4-picture test.



Technical corner: diffraction limit and CTF with small pixel detectors

Many integrators use large resolution cameras with very small pixels without considering the actual lens performance. The resolution of a lens is typically expressed by its MTF (modulation transfer function) graph, which shows the response of the lens when a sinusoidal pattern is imaged. However, the CTF (Contrast Transfer Function) is a more interesting curve, because it gives the contrast achieved when a black and white striped pattern is imaged, thus simulating the behavior of a lens when imaging an object edge.

If *t* is the thickness of a white or black stripe in object space, the related spatial frequency ω (usually expressed in line pairs/mm) is computed as

$$\omega = \frac{1}{2t}$$

For any given value of ω the contrasts is computed as:

$$Contrast = \frac{I_w - I_b}{I_w + I_b}$$

where I_w (intensity of white) and I_b (intensity of black) are the maximum and minimum intensities you can measure on the image plane, for white and black stripes respectively.
CTF is limited by diffraction and the limit lowers with increasing F/#s: for a given spatial frequency ω, the CTF increases when the working F/# gets smaller.
At the same time, CTF also depends on the wavelength range: the shorter the wavelength, the higher the CTF. Expressing the CTF as a function of these parameters yields the following:

$$CTF = CTF\,(\omega, WFN, \lambda)$$

Where ω is the spatial frequency, WFN is the working F/#, λ is the wavelength

the “cut-off frequency” is defined as the ω value for which CTF is zero which occurs when

$$\omega_{cutoff} = \frac{1}{WFN \cdot \lambda}$$

For instance, a TC Series lens with working F/# 8 and operating with green light (λ = 0.000525 mm) has a cut-off frequency of:

$$\omega_{cutoff} = \frac{1}{8 \cdot 0.000525} = 238\,\frac{lp}{mm}$$

Unfortunately, not everyone knows that the camera sensor contributes to the MTF of the whole system with a transfer function of its own. The function trend is approximately sinc(ω) and its cutoff frequency is inversely proportional to the pixel size:

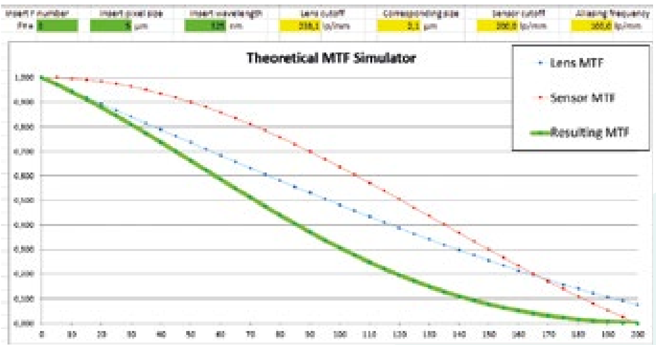
$$\omega_{cutoff} = \frac{1}{p}$$

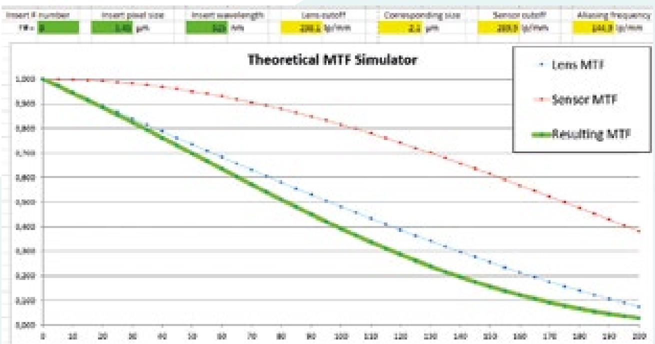
For example, two sensors with 5 and 3.45 μm pixels will have the following cutoff frequencies:

$$\omega_{cutoff} = \frac{1}{0.005} = 200\,\frac{lp}{mm} \qquad \omega_{cutoff} = \frac{1}{0.00345} = 290\,\frac{lp}{mm}$$

This means that the smaller the pixel size, the better the MTF. Using small pixels improve the overall system resolution, since the total MTF is given by the product of the single MTFs (in this case we’re only considering the camera and lens - see the pictures below). Small pixels are also helpful in reducing noise and better defining the profile of an object because the edge detection is carried in two dimensions - therefore decreasing the pixel size strongly increases the number of pixels over a certain image area and makes the edge detection more accurate.

Needless to say, small pixels also offer many drawbacks: they usually bring lower dynamic range and less quantum efficiency (i.e. the capability to efficiently “capture” light). Also, many lenses can’t resolve too small pixels (i.e. 2.2um or less) even at their maximum aperture, meaning that we would achieve the same practical result as if we were using a lower resolution sensor with larger pixels.





Application case #2 measurement of multiple-size screwed

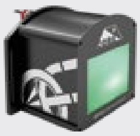
APPLICATION

The application consists in the offline measurement of screws with the same shape (see picture on the right), but of 3000 different sizes. Specifically, the diameter and the tread pitch of the screws had to be gauged with an accuracy of 100 um or better.

SETUP

TCCP3MHR192-C
Ultra compact bi-telecentric CORE lens
for matrix detectors up to 1/1”, magnification 0.064x

RT-MVBF3-2124aG
USB3 Vision camera with Sony Pregius CMOS sensor IMX304, mono



LTCLCP192-G
Space-saving telecentric illuminator for LARGE FOV systems, minimum beam shape dimension 220 x 160 mm, green

CBUSB3001
Passive USB 3.0 cable, industrial level, horizontal screw locking, 3 m

SOFTWARE

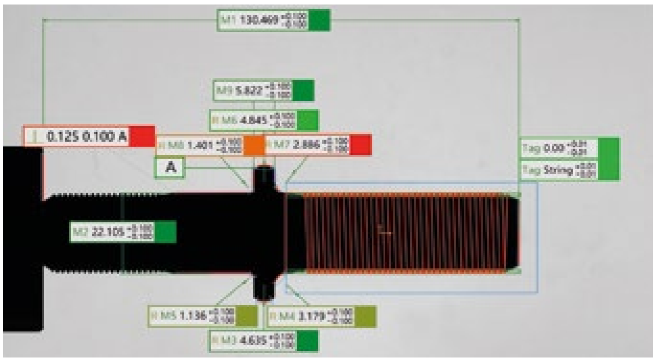
Images were processed with Horus, a metrology software application delivering unmatched measurement accuracy thanks to its state-of-the art calibration algorithms and protocols.

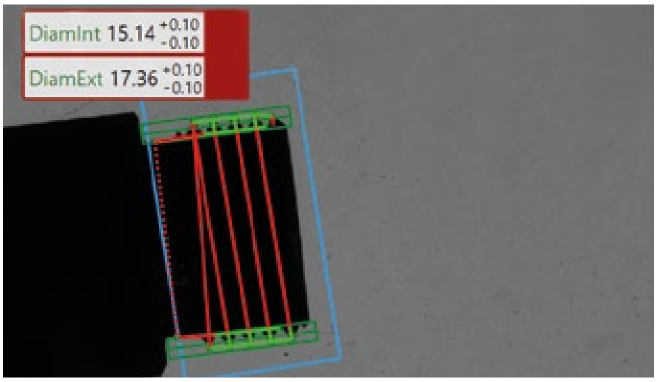
RESULTS

All of the measurements achieved an accuracy better than 100 um according to the requirements.

MEASUREMENTS

The diameter and the thread pitch of different sized screws were measured.





Opto Engineering® products for metrology

OPTICS

Outstanding optical performance.
Unmatched customer service.

TELECENTRIC LENSES

Enjoy the classics! More series available for higher resolution cameras

TC series
Bi-telecentric lenses for matrix detectors up to 2/3"

Who said that a telecentric lens is bulky? Now covering FoVs up to 200+ mm! Models for higher resolution cameras are available.

TC CORE series
Ultra compact bi-telecentric lenses up to 2/3"

TC CORE PLUS series
Ultra compact large FOV telecentric lenses for matrix detectors up to 2/3"

Keep the accuracy on large and small features with a zoom lens! Easily controlled using the Opto Engineering® MTDV motion controller and any software including FabImage, our data-flow based software designed for machine vision engineers!

TCZRS series
8x bi-telecentric zoom lenses with motorized control

MTDV
Motion controller for bipolar stepper motors with additional encoder input

FABIMAGE
Machine vision software and libraries

For small FOV applications: because size doesn't matter, but magnification does!

TCLWD series
Long working distance telecentric lenses for 2/3" detectors

Why waste space for a round lens, when you're imaging a linear Field of view?

TC4K series
Flat telecentric lenses for 4 k pixel linescan cameras

LIGHTING

You know the saying: behind every successful metrology application there is a telecentric light!

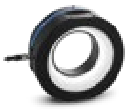
TELECENTRIC ILLUMINATORS

LTCLHP series
High-performance telecentric illuminators

LTCLHP CORE series
Ultra compact telecentric illuminators

LTCLHP CORE PLUS series
Space-saving telecentric illuminators for large FOV systems

Front, back, side, coaxial, low angle, bar, dome and ring lights... you name it! We got your back, regardless of the light geometry, intensity or color.



LED ILLUMINATORS
Advanced lighting solutions.

CAMERAS

Dive into the Opto Engineering® camera offering: low to high resolution, small to large pixels, affordable to high end with plenty of advanced features!

SOFTWARE

From the best hard-coded metrology library taking care of optical distortion and hardware setup - TCLIB - , to an easy- to-use, fully equipped metrology application - HORUS, all of your software needs are covered at Opto Engineering®!

TCLIB Suite
Software library & stand-alone tools for the optimization of telecentric setups

Horus
Windows OS desktop application for optical measurement

Company profile

Opto Engineering® was born in September 2002, founded in Mantua by Claudio Sedazzari, Andrea Bnà and Andrea Vismara. The founding partners have gained a long-standing experience as consultants in the field of machine vision. The newborn company starts to operate in the field of industrial optics by providing design services to companies in a variety of fields such as machine vision, sensors, lighting, lasers, safety and electro-medical equipment.

By intercepting a growing demand for non-contact metrology systems, Opto Engineering decides to develop its own range of lenses for metrology applications with an original and innovative design. Italian customers starting to look at this kind of applications immediately demonstrate interest and appreciation for the new product offering by Opto Engineering, THE TELECENTRIC COMPANY®.

Opto Engineering THE TELECENTRIC COMPANY has evolved through the years, releasing hundreds of new, diverse products and developing multiple areas of expertise. Today we can say that we specialize in OPTICAL IMAGING TECHNOLOGIES.
Our focus is to build and provide every single component needed to solve imaging applications: starting from the optical know-how and going through competence in lighting we can supply the best combination of tools available on the machine vision market.
For all these reasons Opto Engineering® has become the partner of choice in high-end optical applications for many of the major machine vision companies worldwide. Opto Engineering, OPTICAL IMAGING TECHNOLOGIES.

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