VIDEO CAMERA FOR HIGH-PRECISION MEASUREMENTS

Research Scientist Mats Carlin
Optical Measurement Systems and Data Analysis
SINTEF Electronics & Cybernetics
Box 124 Blindern, 0314 Oslo, NORWAY
E-mail: Mats.Carlin@ecy.sintef.no
http://www.sintef.no/ecy/7210/

INTRODUCTION

During the last few decades low-cost semiconductor camera sensors have emerged. These cameras can be used for a number of different measurement techniques based on machine vision measurement systems. We start by describing the important parts of a machine vision measurement system and how each factor influence high-precision measurements. The main applications are found within metrology where dimensions and geometry are measured very accurately and fast, but we will also give examples of other measurements for colour, spectrometry, reflectance, vibrations, texture and even measurements taken inside materials or objects.

MACHINE VISION SYSTEMS

Our definition of a machine vision system is a system for measurement, inspection or surveillance based on connecting an electronic camera to a computer. This presentation is restricted to machine vision measurement systems.

To be able to build successful machine vision systems one must control the following technologies and parts of a machine vision system.

- Lighting
- Optics
- Camera sensor
- Electronics
- Image processing
- System integration

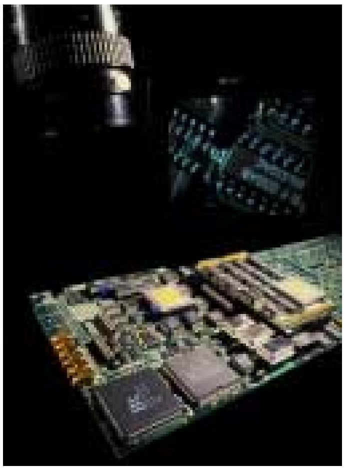

Figure 1: Machine vision systems (Photo: Jan D. Martens)

Lighting

One main issue is to have full control of the lighting in an optical measurement system to achieve the proper image quality. The lighting should be designed to enhance the measurement of the wanted properties. There is a number of important design factors for lighting:

- Intensity
- Spatial distribution
- Spectral distribution
- Temporal variation
- Temperature sensitivity
- Infrared radiation
- Shielding against unwanted light

Without the proper images, we may spend awful amounts of time and money to obtain reliable measurements.

Optics

The optics is crucial for many machine vision systems. The optics is designed to collect and focus the incoming light on the sensor. Important effects of the optics are:

- Geometric aberrations
- Colour aberrations
- Collimation
- Optical transfer function (spatial resolution)
- Projections
- Special effects (filters, gratings, mirrors, beam-splitters, micro lenses etc.)

To obtain high-precision measurement some of the optical effects must be corrected either by calibration or by expensive optics.

Camera sensors

The semiconductor camera sensors are based on arrays or matrices of light sensitive elements called pixels. Silicon is light sensitive in the visible (VIS) to near infrared (NIR) part of the electromagnetic spectrum (300-1000 nm). Other semiconductors are sensitive in other parts of the spectrum, ultraviolet (UV), mid infrared (MIR) and far infrared (FIR). Using special layers called scintilators the semiconductors can even be made sensitive to X-ray radiation. Since applications in the visible part of the spectrum proliferate, silicon sensors are the most common ones. Many of these sensors have an IR-filter that removes all light above 700 nm to avoid special effects in the NIR part of the spectrum. One example is that residual washing powder in clothing is visible in the NIR.

Charged Coupled Devices (CCD) are most common today, while Charge Injection Devices (CID) and Metal-Oxide Semiconductors (MOS) are used for special purposes. The CCDs allow efficient transfer of the electronic charges from the sensor elements to the read-out electronics by a principle called bucket brigade where the charges are shifted from sensor element to sensor element on the chip itself.

The future trend is towards CMOS sensors that can be produced by the same production process as ordinary microchips, allowing cheap sensors with the possibility of integrating processing power directly on the sensor chip. CMOS sensors allow direct access to selected pixels or clusters of pixels on the chip, integration of the camera control electronics on the chip itself and even specialised processing.

Line sensors consist of a single array of sensor elements, while area sensors consists of a grid matrix of sensor elements.

Important characteristics for high-precision measurements are:

- Pixel ratio and area
- Pixel sensitivity, gain and saturation
- Fill factor (percentage of light sensitive area for each pixel)
- Pixel-to-pixel variation
- Dark current (background electronic noise)
- Smear and blooming
- Electronic shuttering (controlling exposure)
- Sensor alignment with respect to the optical axis

Some of these objectives are not possible to combine. 100% fill factor sensors do not allow electronic shuttering, but require mechanical shuttering or strobe (pulsed) lighting, as an example.

Electronics

After exposure each pixel in the sensor has an electronic charge corresponding to the total intensity of the incoming light during exposure. This electronic charge must be read out from the sensor, amplified and digitised, converting the analog electronic charges to digital signals that can be stored and processed on a digital computer.

The trend is to put more and more of the electronics into the camera. Several machine vision cameras offers digital output and even frame-buffers which allows storage of several to a few hundred images before transfer to the computer. The next giant step is to move general-purpose processors into the camera, making them into "smart cameras". Several producers offer such solutions today based on special-purpose processors.

Figure 2: MS900 - A frame-grabber for machine vision (Photo: Jan D. Martens)

The electronics introduce many new effects that we must be aware of and control.

- Dynamic range of the digitisation
- Gamma-factor (non-linear corrective gain)
- Digitisation noise
- Synchronisation and timing of read-out and exposure
- Jitter (line-to-line synchronisation)
- Transmission noise
- Automatic gain control
- Automatic white balance
- Automatic colour correction

Originally the pixels do have a linear light response function, but the electronics may distort the signal from the sensor. These distortions should carefully be avoided in high-precision measurement systems.

Image processing

The images from a machine vision measurement system must be processed to extract the measurement information. The main task of the image-processing module is to transform a digital image to a set of invariant measurements. Several image-processing modules are necessary in most measurement systems.

- Calibration routines
- Routines for identification of the position and rotation of the objects and measurement areas
- Robust and accurate measurement routines based on the physics of the measurements
- Statistical treatment of the measurements
- Error identification and handling

There is a trend towards performing the image processing on general-purpose processors, not special-purpose processors. It is of utmost importance to keep the image processing as simple as possible.

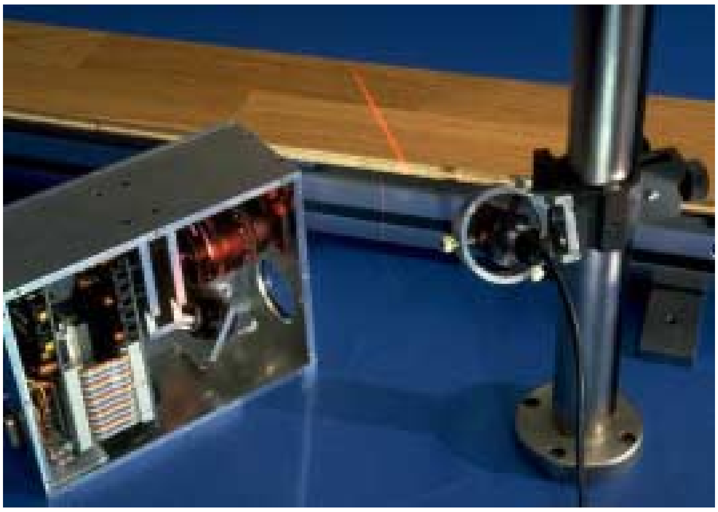

Figure 3: Parquet-floorboard inspection by smart camera (Photo: Jan D. Martens)

System integration

Most machine vision systems for high-precision measurements are an integrated part of a larger inspection or quality control system. The machine vision system must be able to communicate in real-time with the other parts of the system to report results, initiate actions like sorting or rejection of the measured objects and build reliable measurement models. In addition the equipment must meet certain environmental standards to endure varying mechanical stress, temperature, vibrations, electromagnetic noise and air quality (dust, dirt etc.).

Advantages of machine vision systems

- 100% inspection and control
- Objective measurements
- Non-contact measurements
- High accuracy
- High capacity
- High flexibility, reprogramming is possible
- Traceability
- Scalability
- System duplication is straightforward
- Mass production is relatively cheap

Disadvantages of machine vision systems

- Development costs are often high
- Most systems are custom-designed
- Many error sources require extensive expert knowledge
- Our eyes have higher precision in some cases
- The systems solves other problems than those that humans excel in
- Inability to interpret and understand natural scenes
- No automatic decision making when unprecedented situations occur
- Occlusion can normally not be resolved
- Regular maintenance is often necessary

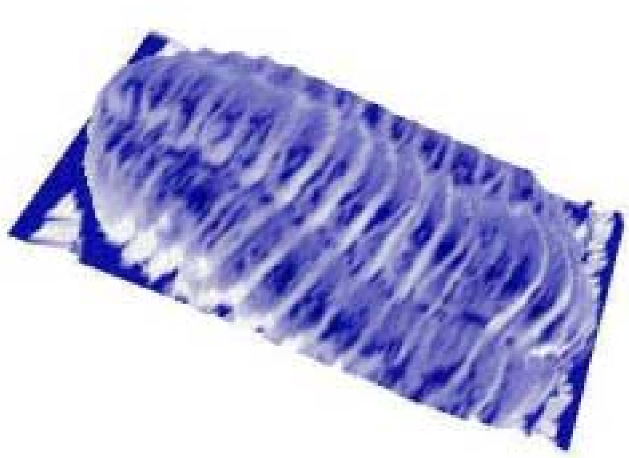

Figure 4: Trilobite scanned with laserplane triangulation

METROLOGY (HIGH-PRECISION GAUGING)

Metrology is the science and technology for high-precision measurements, in our case of the shape and geometry of objects. We will start out by the basic principles of some simple measurements and proceed with more complex measurement techniques.

Ruler-based measurements

The input obtained from a line sensor or by extracting a line of consecutive pixels in an area image is suited for ruler-based measurements. Rulers measure the relative distance between the edges or artefacts of objects or the absolute position along the ruler with respect to a reference point.

Any pixel value transition along the ruler indicates a change in intensity in the image. Intensity changes indicate edges of the objects in the image. The image of a sharp edge can be modulated to stretch over several pixels. The smooth transition allows subpixel measurements of the position of the edge.

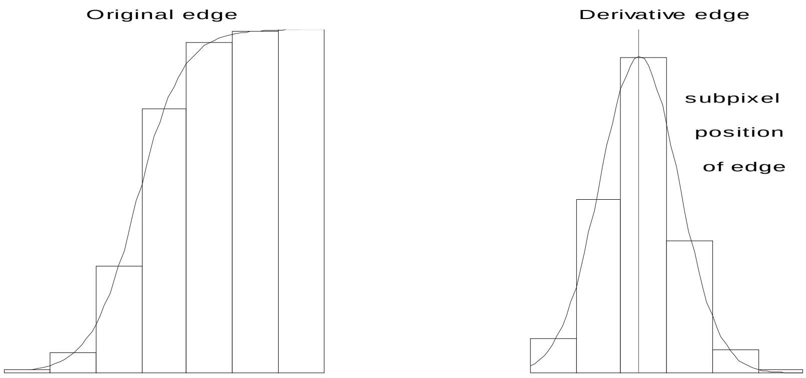

Figure 5: Subpixel position of edge based on signal processing

For 8 bit pixels with full dynamic range for the imaged transition from black to white through 256 possible pixel values over 5 pixels, the theoretical measurement accuracy is about 1/128 pixels. Laboratory experiments at SINTEF Electronics & Cybernetics confirms that it is possible to achieve close to theoretical accuracy in the laboratory under controlled conditions. We have achieved an accuracy of 1/20 pixels under factory conditions on a gauging system measuring the diameter of an airbrake-fitting ring at Raufoss AS.

Figure 6: Inspection of air-brake fittings at Raufoss AS (Photo: Jan D. Martens)

Since some line sensors have up to 8000 pixel elements, the theoretical upper bound of the relative accuracy of ruler-based measurement systems is in the range of 1/800 000 of the measurement area (field-of-view). This is only valid if the spatial resolution of the optics admit such accuracy.

Using ordinary optics require that the objects has a fixed focal distance from the measurement system. Collimating the light by collimators on the light source and/or telecentric optics allows a more flexible measurement distance range.

Diffraction-based measurements

For objects that are smaller than the pixel size (threads, fibres or small particles), we may use the diffraction patterns of the object. We use a collimated light source for this purpose. The diffraction pattern will reveal the position and the size of the object with subpixel accuracy.

Measurement of planar shape

The planar shape of an object is the geometry of a 2-dimensional projection of the object. It is possible to extend the ruler-based approach to measure the 2-dimensional shape. A greyscale image can be seen as a 3-dimensional surface. By following the ridges and slopes of this surface placing rulers perpendicular to the path of the slope or ridge, we may measure the shape of an object with subpixel accuracy. These measurements can be used to detect errors and deviations from a fixed or flexible production template. Deduced measurements of angles, length of edges or areas can easily be made.

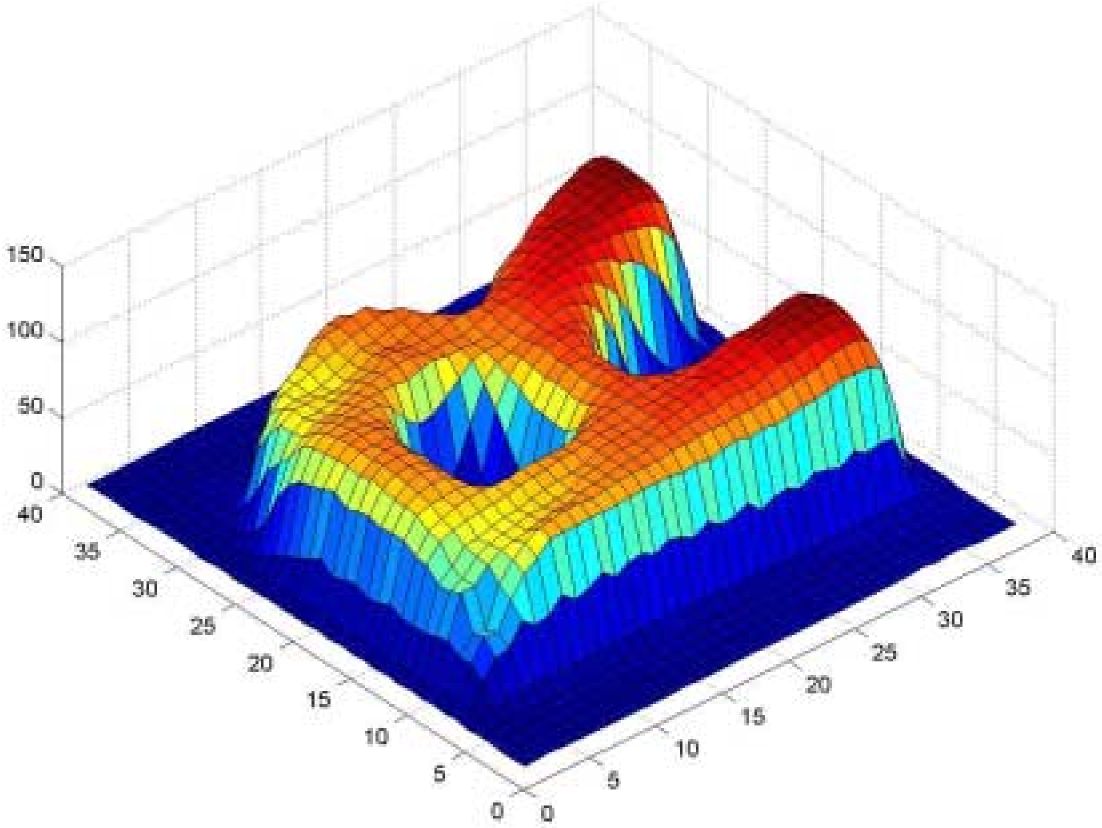

Figure 7: Height plot of the letter R on a cellular phone display window from Iplast.

Triangulation and measurement of 3-dimensional surfaces

Many objects do have a 3-dimensional shape that we wish to measure. We can use triangulation principles to achieve this purpose. This basic principle has been used for at least a century to determine the height of mountains and for geographical surveys. The modern field of technology is called photogrammetry, measuring geographical positions in airborne and satellite photos.

There are two common alternative triangulation principles used in machine vision applications.

- Using several cameras at known relative positions (stereovision)
- Triangulation by structural lighting

To obtain accurate measurements of 3-dimensional surfaces using several cameras require that we place markers on the surface. These markers are then detected and positioned in each of the images. Since we know the relative position and rotation of each camera, we can resolve the exact position of the marker in three dimensions by triangulation. Metronor AS has developed a special light pen marker that can be pointed onto any surface to trigger a triangulation. Successive measurements result in a 3-dimensional surface model of the object. Reflective markers are used for measuring deformation of cars during crash tests.

The second principle is based on structured lighting where a fixed light pattern is projected onto the surface and images taken by a camera with a fixed relative position and rotation with respect to the structural light projection. These patterns include points, lines grids, circles and edges. Lasers are particularly suited for this task since they are easily beam-shaped, collimated and are stable light sources. Since a laser emits light at only a single or a few wavelengths, it is easy to apply an optical band-pass filter to extract only this wavelength, reducing the problem of shielding unwanted light sources. Diode lasers are cheap and compact, have long lifetime, low power-consumption and can be pulsed with high precision. Care should be taken to ensure that the lasers are eye-safe as the eye may be damaged if directly exposed to laser light above certain intensities and pulse-widths.

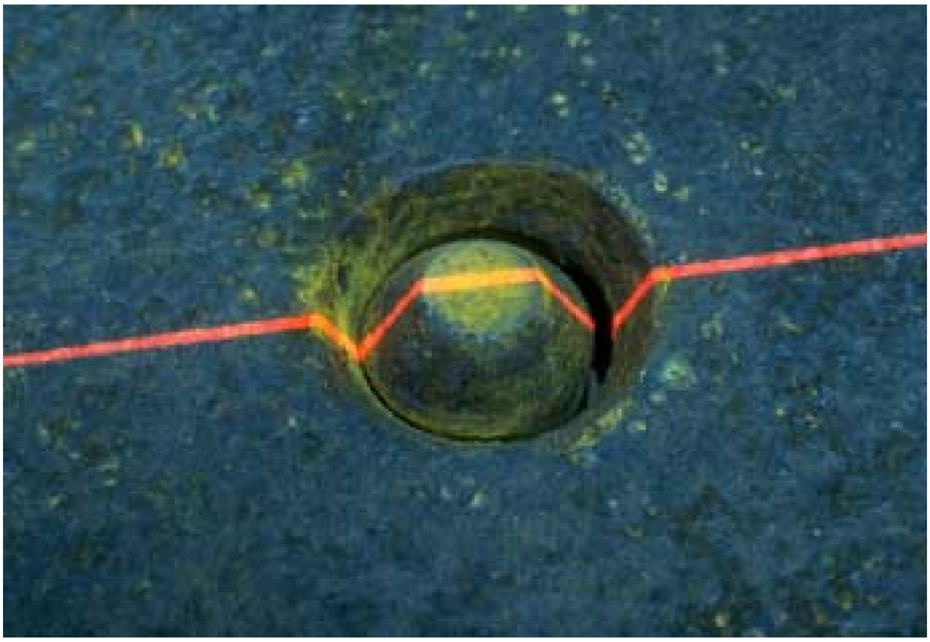

Figure 8: Laser plane projection onto a steel bolt (Photo. Jan D. Martens)

At SINTEF Electronics & Cybernetics we have long experience using laser plane triangulation where a single line is projected onto an object passing through the field-of-view in a linear motion. We have measured the surfaces of as diverse objects as trilobite fossils, parquet floorboards and glowing steel blocks at 700 degrees Celsius. Subpixel techniques can be used to obtain high precision measurements.

Interferometry

In interferometry the wave nature of light is utilised for measurement of object properties. A wide range of techniques exists, but a common feature is that the illuminating light beam is split in two beams that are combined at a later stage. White light interferometry can be used for topography measurements on a microscopic scale (x~50 μm – 2 cm) with high vertical resolution (Δz~1 nm). However, most interferometry-based methods use monochromatic light and rely on changes in fringe patterns or phase changes. One example is TV-holography (electronic speckle pattern interferometry) which is used for subsurface inspection, deformation and vibrational analysis of macroscopic objects.

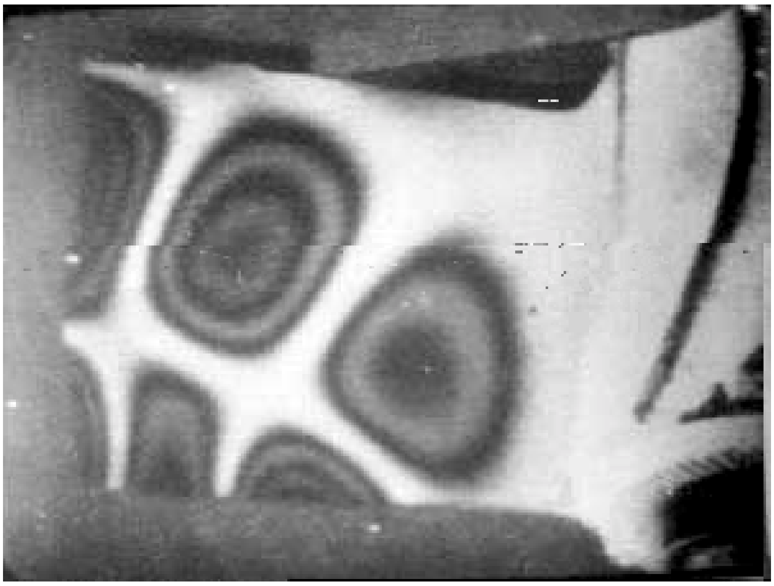

Figure 9: Vibration pattern found by interferometry (Courtesy of SINTEF Materials Technology).

Geometric calibration

To ensure precise measurements we must calibrate the geometry of the sensor and the optics to remove geometric aberrations of the optics and sensor displacement and rotation with respect to the optical axis of the optics. A calibration object is placed in the measurement plane or volume and a calibration model can be built mapping the every point on the sensor to a position in the measurement zone. Typical calibration objects are slits with known positions for line sensor and plates with gridded holes or markers with known positions for area sensors. Laser plane triangulation can be calibrated by fixed profiles with known section geometry placed in the movement direction.

The shape and ruler-based measurement techniques also require an even spatial light intensity distribution. For very high precision measurements the gain of each individual pixel is calibrated to correct for uneven spatial intensity distribution.

Colourimetry

Colour is the human perception of the spectral distribution of the light reflected, refracted, transmitted or emitted by an object.

Colour cameras mimic our perception of colour by using red, green and blue optical band-pass filters. Two alternative colour camera types exist, 3-CCD colour cameras and colour filter cameras. The 3-CCD colour cameras use beam-splitters to direct even portions of red, green and blue light to three individual CCD sensors. The main advantage is high sensitivity and that the three colour channels are measured for exactly the same position on the measured object. A single CCD colour camera does have a special pattern of colour filters attached in front of the individual pixel. Afterwards the pattern is mixed and resampled to obtain colour measurements. Cheap colour cameras tend to have a large degree of overlap between the three colour channels. In colourimetry the RGB signal is transformed to a colour space spanned by the hue (distinct colour), saturation (colouredness) and total intensity of the signal.

Accurate colour measurements are very difficult due to a number of reasons. Two objects with the same perceived colour may have widely different spectral characteristics, but with the same amount of total intensity in all three colour channels. Two objects with a relatively small difference in spectral characteristics may be perceived to have distinct different colours. The spectral distribution of the light source interacts with the material of the measurement object. Different light sources may result in different perceived colours. The spectral distribution of many light sources varies with the temperature and over the lifetime. The angle of the incoming light may result in different perceived colours.

To obtain high-precision colour measurements we should use a temperature-stabilised light source and an integrating sphere to achieve controlled and evenly distributed diffuse lighting. Careful colour calibration with known time-stable colour templates must be made and the colours should be corrected for temperature variation and the interaction of the reflected light from the object and the integrating sphere (colour displacement).

Spectrometry

In many applications we wish to identify the chemical composition of the objects. Since most materials and gases have distinct spectral characteristics, spectrometry can be used as a tool for material and gas characterisation. By placing a slit and a grating or prism in the optical path of the measurement system we may spread light with different wavelengths in one direction. Using a line sensor we obtain a point spectrometer, but by using an area sensor we obtain a line spectrometer, which decompose the signal in a spatial and a spectral axis. This technique can be used to measure the extent of certain materials with certain spectral characteristics.

By careful examination of the electromagnetic spectrum special optical band-pass filters may be designed to allow for an image in a few spectral bands, enabling us to distinguish between different materials. SINTEF Electronics & Cybernetics has developed a system for plastic and cartoon waste handling for the Norwegian company TiTech Autosort. The system is able to distinguish between all the important plastic types in the waste stream enabling efficient handling of plastic waste. Most materials are however easier to distinguish at optical wavelengths above 1000 nm and we may not use CCD sensors directly, but must turn to other semiconductor sensors.

Measurements of light scattering

For some materials the light scattering properties are of great importance. One example is lighting reflectors that may vary from glossy specular reflective materials, semi-diffuse materials to matte diffuse materials with a scattered reflection. SINTEF Materials Technology has developed equipment for exact measurement of the scattering of aluminium reflectors based on the spatial distribution of the reflected light of a laser point hitting the material to be measured. The scattering measurements actually tell something about the roughness and microscopic surface structure of the material. Light scattering measurement is also used for quality control in production and to follow dynamic processes.

Texture measurements

Texture is the homogeneously repeating spatial intensity variation over an area on the surface of an object. Some materials do have a distinct texture that characterises another property of the material. Many food types have different taste and consistency dependent on the texture of the food. At Matforsk extensive experiments have been done on different types foods correlating the texture of the food with different perceptual markers such as consistency. Similar measurements can be done on objects like textiles and plants, measuring the wear of the textile or the growth rate of the plant.

Counting

In some applications we wish to count the number of objects in the field of view. One example is bacterial counts on petri dishes. Efficient statistical techniques exists allowing us to sample the petri dish at a few locations and estimate the bacterial count based on a model based on the shape of each bacteria, the probability of occlusion and the overall distribution on the petri dish. Other applications do have similar requirements to estimate the number of objects or the total volume or quantity of the specific goods.

Measurements inside objects

Even when the measurable property is inside the measured object, certain techniques may be applied to obtain accurate measurements.

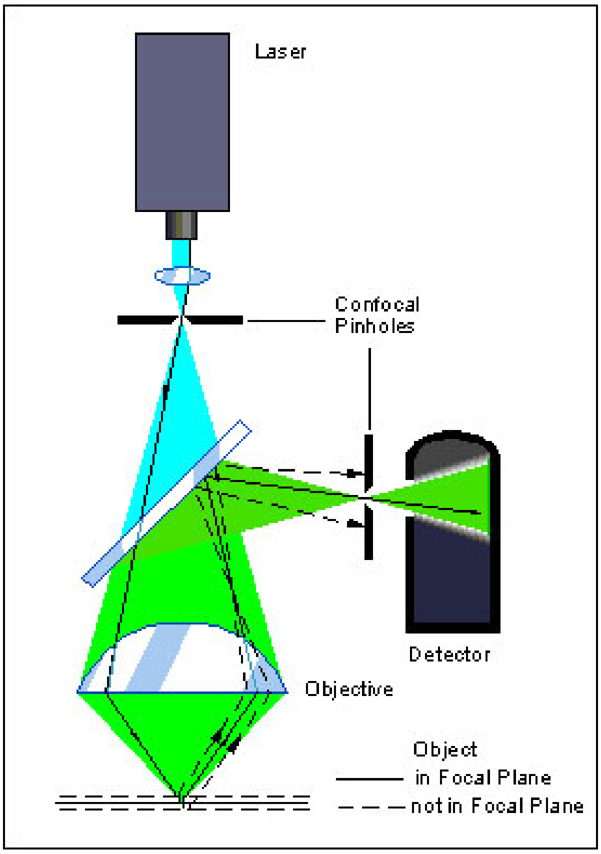

Figure 10: Basic principles of scanning confocal microscopy.

For semi-transparent and porous objects like biological material or paper, measurements can be made inside the material using techniques like scanning confocal microscopy. Scanning confocal microscopy is based on sectioning the material optically slice by slice and builds a 3-dimensional model of the sample. In these 3-dimensional models high-precision measurements can be performed. One example is to measure fibre length, diameter and directionality of paper and correlate these measure to physical properties of the paper such as print absorption, mechanical shear strength etc. The link to research in X-ray computer tomography, nuclear magnetic resonance imaging and ultrasound measurements on biological tissues are obvious.

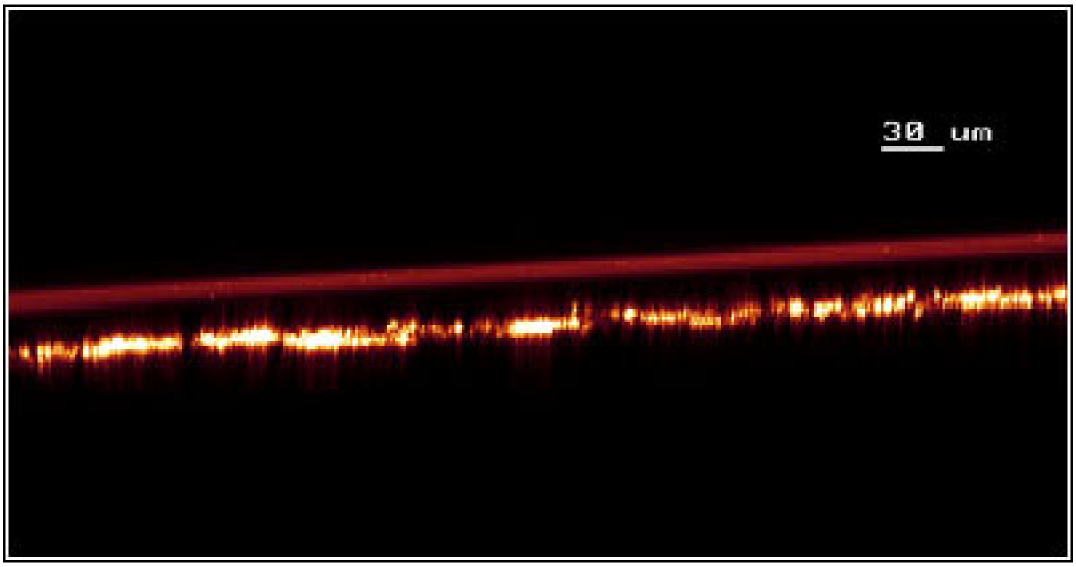

Figure 11: Detecting metallic particles 30 microns below the surface of a metallic lacquer.

One could expect that solid materials are much more difficult to examine inside with optical techniques, but some possibilities exist. Laser-excited thermography is one technique that may be used to measure structures inside solid objects. The principle is based on exciting the surface of the object by pulsing a powerful infrared laser. The surface is heated fast and by measuring the cooling of the object using an infrared camera, we get a temporal measurement of the heat transfer properties of the material. Internal details and defects of the material can be detected and measured since these change the heat transfer properties of the object. This technique is as an example used for measuring micro-cracks in machinery, as an alternative to X-ray imaging which is unable to measure the smallest cracks.

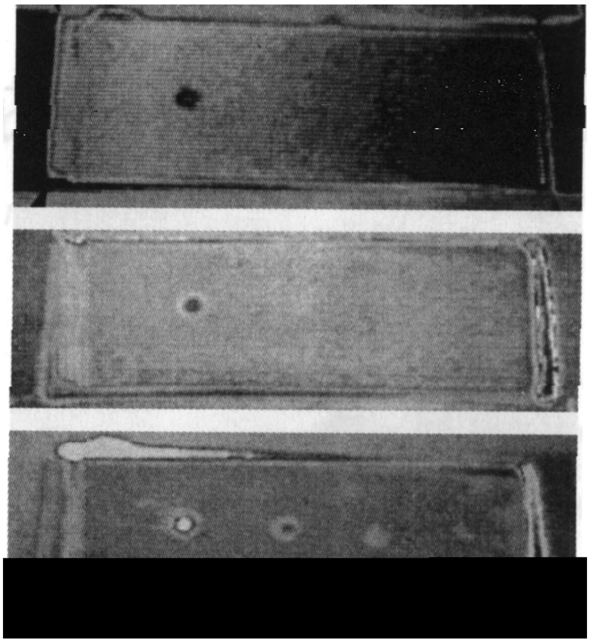

Figure 12: Detecting internal defects in a material using pulsed laser thermography

SUMMARY

In this presentation we have a presented a number of high-precision measurement techniques based on CCD camera sensors and machine vision technology. Important factors for high-precision measurement have been considered as well as a number of different applications of these measurement techniques, spanning metrology, colourimetry, spectrometry, scattering measurments and measurements inside solid, oblique and structured objects.