Cameras for near infrared spectroscopy

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Introduction

Cameras can bring new opportunities to near infrared (NIR) such as NIR mapping or multichannel spectroscopy. In mapping, the camera is used conventionally, but the light—normally visible—is replaced by infrared radiation, produced either by filters or by monochromators. In multichannel detection, it is not mapping that is of interest but speed of detection. In both cases, the choice, setting up and testing of cameras are of primary importance. In this paper, we will discuss how to choose a camera for a NIR multichannel spectrometer and we will show how our methodology can be translated into NIR mapping.

First choice is the sensor technology: either tube or solid-state cameras are available. The advantage of tube cameras is that they are more sensitive in the higher wavelength ranges, i.e. above 1100 nm. Indeed, solid-state cameras are generally made from silicon, which is insensitive above 1100 nm. However, tube cameras are less resistant than CCD ones and show more shifts. Two types of electronics are available for solid-state cameras: CCD or CID. CID cameras allow integration of the signal and independent access to each pixel, but are more costly. With CCD cameras, it is important to consider wavelength range, dynamic range and size.

Taking into account these different constraints, we have built a multichannel spectrometer for rapid detection of sugar in fruits. The CCD camera is linked to a Jobin Yvon monochromator, in which fibre optics convey the signal. This system allows for the classification of apples in three categories with 80% success. With these good results, this CCD camera will soon be used to build a NIR system for humidity and fat mapping.

The history of vision systems shows that the concept of vision processing started in the fifties, and became widely used in industry in the eighties.[1] The development of visible vision systems for industry (either mechanical or food industry) has been boosted by the need for more quality control and by higher manpower costs. It has also been made possible because of the large abundance of domestic video cameras—which encouraged the transfer of the technology to industry—and thanks to the explosion of computing facilities. On the other hand, mid-infrared cameras have been developed essentially for military applications (night vision, object tracking) based on thermometric detection (thermocouple arrays). Between these two wavelength ranges, i.e. in the near infrared range, no intensive research on low-cost cameras has been undertaken so far, because of the novelty of NIR spectroscopy and of the lack of awareness of the advantages that NIR can bring.

However, after 40 years of life, NIR has proved its utility as an analytical tool and is ready for a new "technological jump". This jump can be brought about by the availability of cameras

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permitting both NIR imaging and NIR multichannel detection and thus providing robust on-line detectors for food composition analysis.

Surprisingly, NIR imaging is fairly widely used: not in agricultural and food applications but mainly in astronomy, remote sensing and in a secondary way in medicine. In a bibliography of the three last years (ISI database), NIR imaging was cited in 80 articles, 73% of these articles were related to astronomy, 12% to medicine and 15% to various other applications—including agriculture and food. In these areas, NIR imaging is just an emerging technology and literature related to it is very poor. Taylor and McClure[2] used it to detect defects on tobacco leaves by combining images taken at 670, 800 and 990 nm using a CCD camera and a rotating filter wheel or to determine water depth. Robert *et al.*[3] used a tube camera combined with a monochromator to discriminate between different components of cereal (starch, gluten and bran). Bellon *et al.*[4] have also shown, in a previous study, how the combination of both visible and NIR wavelengths enabled them to detect defects on apples, whereas detection was impossible using only visible light. In a similar approach, Upchurch *et al.*[5] combined NIR and imaging to detect bruises on apples.

In this paper, we would like to show what can be achieved in agriculture with the cameras presently available, both for imaging and for multichannel detection, i.e. we will detail the various cameras suitable for NIR, how to choose them and how to implement them to construct a NIR imaging or multichannel system. Then, we will present one example of a camera used in a multichannel detection system.

Technology of cameras for NIR applications

A camera is a device that directs an image focused by a lens or other optical system onto a photosensitive surface housed in a light-tight enclosure (Grolier encyclopaedia 1995). Available technologies vary according to the type of detection, the type of sensitive material, the geometry of the sensor etc.

Sensor technology

Cathode ray tube

These sensors originate from television technology. The energy of the photons emitted by the scene is transmitted to a photoconducting screen. The energy of each image point is then collected by electronic sweeping. The sensitive surface is swept line by line. The CCIR norm for one line duration is 64 µs.

The advantages of such a camera are:

- Low cost, but beware, in spectrophotometry this is not the case.
- Different sensitivities are available, depending on the photoconductive layers, different wavelengths, different noise characteristics and different resolutions.

The disadvantages are:

- Geometric distortions
- Persistence of the tube
- Not very rugged for industrial uses
- Short life-time

Such cameras are now used only for specific applications where solid state cameras are not efficient or do not exist.

Solid state detector

The principle of solid state sensors is based on the optoelectronic properties of metal oxide–silicon capacitors (MOS). The solid state sensors can be classified according to the type of detection and to the type of charge transfer.

Detection

There are two types of detection:

- Photoconductance: the semiconductor is the point of release of electric loads which enhance its conductivity.

The disadvantages of these components are:

  - non-linearity
  - high time constant
  - ageing phenomena
  - temperature sensitivity.

- Photodiodes: the semiconductor is lit by the incident light which loads a capacitance. This voltage is then transmitted to a second capacitance (MOS). The MOS can also be lit directly. These photodiodes are traditionally used for spectroscopy (InGaAs etc.). Photodiodes are recommended for applications that have a large intensity and require the best signal-to-noise ratio (S/N).

Transfer

The detectors also vary in the way they transfer the charges from the array. Two generic transfer types are available: CID and CCD.

- CID (Charge Injection Device): in this case, each pixel consists of two MOS capacitors, is connected by its own row and column numbers (x–y addressable) and has a non-destructive readout. The charges can be kept or discarded (injected). Non-cooled CIDs have a higher noise but lower blooming than CCD.
- CCD (Charge Coupled Device): The CCD is managed by different clock signals allowing time-delay integration (TDI): long time integration for low light conditions or fast integration for a fast moving scene.

CCDs can be illuminated either from the front or the back. A back illuminated CCD is obtained by removing the substrate material behind the sensitive area. This solution improves quantum efficiency and spectral range (200–1100 nm) but the CCD must be thinner (less than 15 µm) and thus, is difficult and more expensive to fabricate. CCD noise and offset are temperature dependent. New chips include micro-lens arrays, where each pixel has its own lens to concentrate more light. The various transfer types are the following:

Line address transfer: pixel rows are connected in series and one pixel of each row is moved to a shift register which represents a complete line of the image. Because the light keeps on illuminating the sensor during the transfer process it is necessary to shutter the detector (mechanical shutter) which is not very convenient.

Frame transfer: similar to the previous principle, the frame transfer process consists of transferring the whole pixel frame to a secondary array protected from the light; in this case it is possible to grab images as fast as the transfer speed and to generate a video signal at a standard speed (asynchronous process). However, this method requires twice the size of the silicon area and is expensive and difficult to integrate on a small chip.

Interline transfer: this is an enhancement of the line transfer; the charge collected during the integration is transferred to an adjacent storage pixel. This method provides a compact design, a cost-effective solution and a very fast shutter speed (beyond 1/30,000 s).

Sensor geometry (linear, 2D)

There is the choice of a linear sensor or a matrix sensor.

Linear

This kind of sensor is the most common in spectroscopy and is based on a line of small sensors. The time integration depends on the clock speed. Most modern types include an interline transfer mode that provides an electronic shutter mode. Sizes vary from 256 to 8000 pixels. They can be used to take 2D images by moving the object in front of it.

2D sensor

This sensor is based on the area of pixel, the shape can be rectangular or square. Very different sizes of chip are available: rectangular—2048 × 3, 298 × 100 etc. Square—256 × 256 to 5000 × 5000.

Commercially available cameras

As mentioned in the preceding section and if only solid state cameras are considered, the variety comes from the geometry (linear or array camera), from the sensitive material or from the transfer technology. More precisely, the sensitive material is determined by the geometry of the camera.

Materials which are sensitive in the NIR are Si, Ge, PbS, PbSe, InGaAs, GaAs and InSb, as shown in Figure 1. However, the design technology is not the same for all the materials. Thanks to the abundance of domestic video cameras, Si sensors are by far the most developed. These detectors are available in linear or array shape, with various numbers and sizes of pixels (see preceding section).

The dynamic range of Si vision systems also varies from the typical 256 grey levels (8 bits) for classical vision cameras (Sony, Japan) to around 65,000 levels (16 bits) for special spectroscopy cameras (EG&G, USA; Princeton, USA; Hamamatsu, Japan; Graseby, UK). Because of the large effort made on these materials, Si cameras are NIR cameras with the least cosmetic defects. They

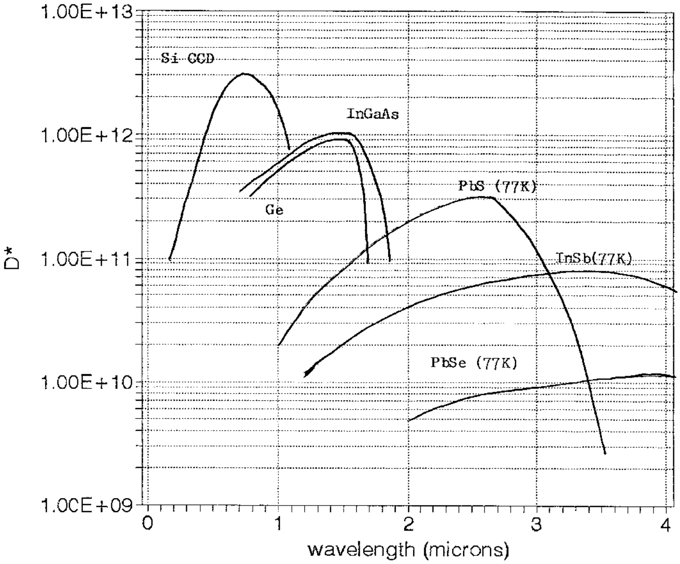

Figure 1. Detection ranges of NIR sensitive materials.

are generally thermoelectrically cooled. Their costs vary from around $1000 for the basic ones to $6–7000 for the most sophisticated ones.

Ge cameras are now available in linear form, with 128 or 256 pixels (Hamamatsu, Japan; Princeton Instruments, USA; Graseby Infrared, UK) and with 100 µm × 2500 µm sizes (with 100 µm gaps). The arrays are cooled with liquid nitrogen in order to minimise dark charge for an integration time of several seconds.

InGaAs detectors are thermoelectrically cooled to reduce the dark current. Devices are typically composed of 256 elements, each 30 µm × 100 µm and with 50 µm spacing (Princeton Instruments, USA). They are also available in a matrix arrangement, 128 × 128 and cost between $25,000 and $40,000 (Princeton, USA; Graseby Infrared, UK). The advantage of InGaAs stems from its tuneable alloy composition, which allows its dark current to be tailored to the desired cut-off wavelength. For instance, the standard $In_{.53}Ga_{.47}As$ covers the spectral range of 0.9 to 1.7 µm, and "extended" wavelength $In_xGa_{1-x}As$ involves the use of higher indium content alloys that detect light out to 2.5 µm.[6] These detectors have been used in NIR spectroscopy for the assessment of glucose content in blood and for intruder detection.

PtSi devices are arrays of 1024 elements, each element being 25 × 2500 µm. The detector is sensitive to the 1–5 µm range and is cooled by liquid nitrogen. They are used in thermography applications. David Sarnoff Research Center is developing PtSi 64 × 128 and 320 × 244 infrared CCD cameras.[7]

PbS and PbSe devices exist in 64, 128 and 256 elements, with sizes equal to 2.5 × 50 µm, 2.5 × 100 µm and 100 × 100 µm (and element spacing equal to 10 µm). They are also thermoelectrically cooled (Graseby Infrared, USA). They are photoconducting arrays and thus suffer from slow speed, high noise and high-voltage supply.

The new technology pushes the limits into two major areas: the read-out speed and the dynamic range. It is now possible to find CCD arrays with read-out rates equal or superior to 900 spectra per second. It is also common to find devices which offer 12 bit or 16 bit dynamic ranges.

Even if several retailers produce NIR cameras, only a small number of manufacturers produce the chip; major companies are Kodak, Loral Fairchild, EEV, Reticom, SITe (Tecktronix), David Sarnoff Research Center (formerly RCA Laboratories), Mitsubishi, NEC, Princeton Instruments, Graseby Infrared, Hamamatsu.

How to use a NIR camera

The use of a CCD camera in a project should be achieved in two phases:

- Definition of the sensor requirements
- Mounting of the camera in the whole system, i.e. wavelength selection technique.

Definition of the sensor requirement

Anyone starting a NIR imaging or multichannel spectroscopy project should choose the camera after having considered the following points:

Definition of the project

Define your problem, the objectives and your needs:

- Application domain (video or spectrophotometry)
- Spectrum requirement
- System portability
- Speed requirement
- Cost of the project
- Who will use the camera and the system?

- Which computer will analyse the signal?
- Do you need a specific frame grabber?
- Do you need a large amount of memory?
- Do you need to acquire numerous large images?

Definition of the sensor features

- Shape of the sensor (linear, 2D)
- Optimised coating for NIR application
- Format (aspect ratio, size of pixel etc.)
- Spectral response
- Cooling necessity
- Video standard compatibility (speed transfer)
- Number of defect points (for large array)
- Pixel clock
- I/O connectors
- Selection of appropriate lens
- Size of the camera (standard, compact, module etc.)

Wavelength selection

Imaging technology

In imaging technology, wavelength selection can be achieved in the same way as in spectroscopy, i.e. rotating filter, tilting filter, monochromator and lighting with mono-wavelength sources. Rotating filters appear to be the most straightforward mounting. As stated above, they have been used by Taylor and McClure.[2] As in spectroscopy, their limits appear in the availability of interferometric filters and in the lack of reliability of rotating parts. Tilted filters coupled to imaging systems have not been mentioned in the literature. A monochromator has been used by Robert *et al.*,[3] with sampling every 50 nm. In this case, all the wavelengths were available. The problem was the low amount of signal. Another path has been explored by Cemagref which has used the classical configuration of a colorimeter for NIR imaging, "replacing" the detectors by cameras. A 3-array camera, in which filters can be changed, has been designed (Figure 2). By combining visible (red, green) and NIR radiation (800 nm) in this system, it has been possible to discriminate

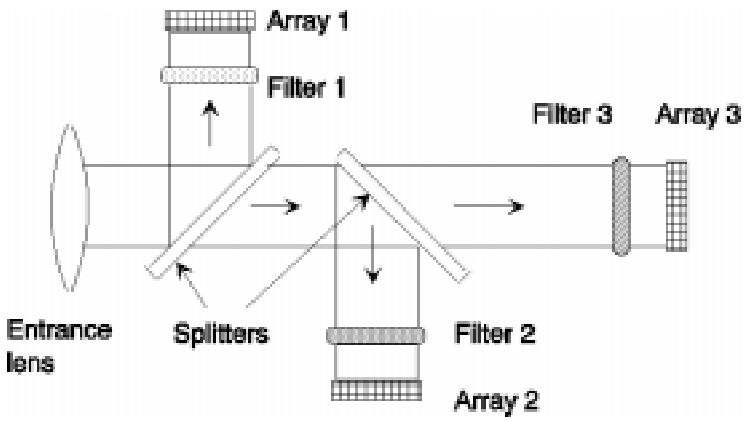

Figure 2. The 3-array camera of CEMAGREF for custom-wavelength imaging.

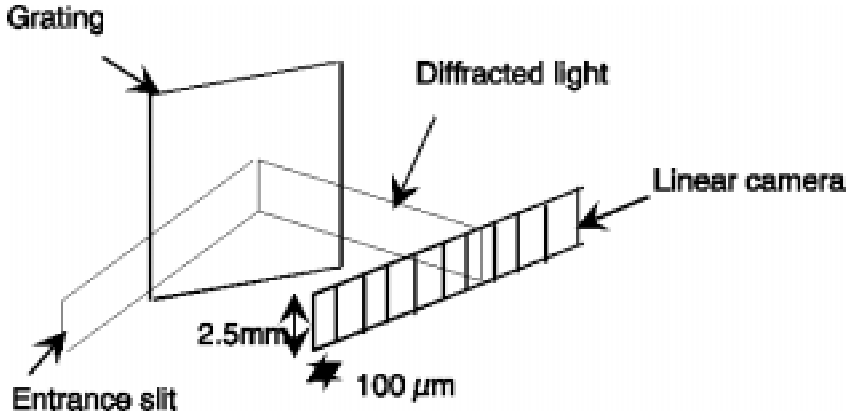

Figure 3. Classical multichannel detection with a linear camera.

between defects and shadow areas on apples.[4] Compared to rotating filters, the advantage of the system is that there are no moving parts.

For imaging, other possibilities should be envisaged, such as the lighting of the sample by monochromatic wavelengths, produced either by lasers or by acousto optic tuneable filters.

Multichannel spectroscopy

In multichannel spectroscopy, the most common design is the monochromating of light emerging from the sample and then simultaneous detection of the various wavelengths by a linear detector (Figure 3). The width of the linear camera must be as large as possible (typically 2.5 µm) in order to have a larger detection array.

If the detector is a 2D detector, it is possible to have both multichannel detection and multipoint detection. This will be described in the following example.

The use of a camera for a multichannel/multipoint detection

The diode array technique uses a grating to separate the wavelengths and a "multichannel detector", either linear- or matrix-type. Whereas linear detectors are relatively common, we have chosen to work with matrix-type cameras in order to develop a multichannel/multipoint detector. In this system, the sample(s) is(are) lit by a halogen lamp via 22 fibre optics; the light emerging from the sample(s) is collected by a 88-fibre-optic bundle; at the entrance slit of the monochromator CP 200 (Jobin Yvon, France) the fibres are arranged in a column. At the detector point, a matrix camera (MICAM HRS) is attached to the flat-field monochromator (Figure 4). The camera is a 500 (h) $\times$ 582 pixel CCD camera, 8.8 µm $\times$ 6.6 µm with 17 $\times$ 11 µm pixels. Its detection capability is still satisfactory in the higher wavelengths (compared to the 540 nm peak, detection capability is 60% in the 800–1000 nm range and 30% at 1050 nm). As the grating diffracts the wavelength range 500–1230 nm (i.e. dynamic range equal to 730 nm) onto a focal plane at 19.3 mm and as the length of the detector is 6.6 µm, the dynamic range is 6.6/19.3 $\times$ 730 nm, i.e. 250 nm. By adjusting the grating, with this dynamic range, the detected range was 800–1050 nm.

The interest in this system is three-fold: (i) the measurement is extremely fast: the camera records 25 images a second, i.e. at least 25 spectra a second; (ii) multichannel detection is achieved and thus the system has no moving parts and is robust; (iii) multiplexing is feasible because the 20 collecting fibre optics are arranged in a column at the entrance of the monochromator, the light

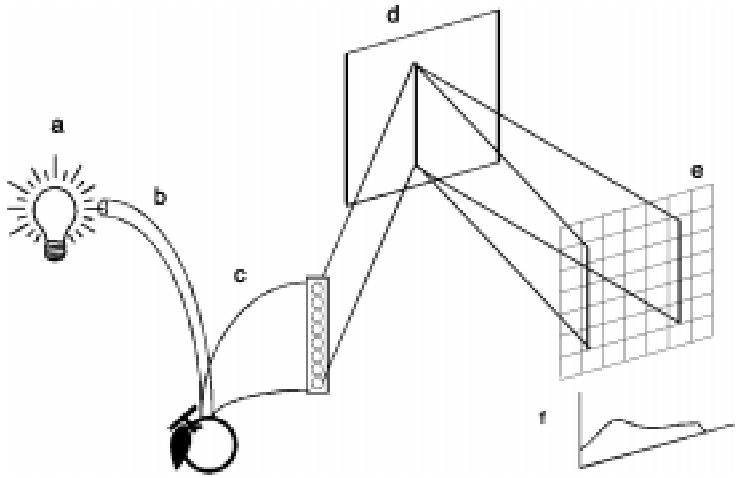

Figure 4. The CEMAGREF array-detector fibre optic spectrometer: (a) source, (b) emitting branch and (c) collecting branch of the bifurcated fibre optics bundle, (d) grating, (e) detector and (f) spectrum.

coming out of the first fibre is diffracted on the first line of detector and the same is true for the other fibres.

Finally, the system is robust enabling 20 spectra to be recorded in a single snap with 25 snaps per second. Thus, the maximum theoretical number of spectra is 500 per second.

This system, used to measure sugar in apples (59 calibration samples and 29 validation samples), enabled us to sort apples in three categories of maturity with an accuracy equal to 83% (Figure 5).

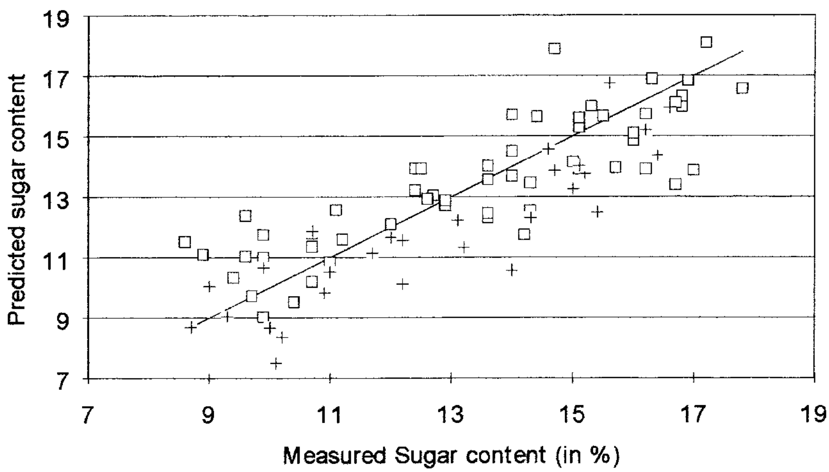

Figure 5. Predicted versus true sugar content (in %) for a calibration and a validation set on smoothed data (❑: calibration sample, +: validation sample).

Conclusion

In NIR, cameras can be used both for multichannel detection and imaging. In multichannel detection, 2D cameras offer the advantage of multiplexing. Thanks to the development of new materials and consequently a reduction in costs, we believe that multichannel detection has a bright future. The future challenges for CCDs are lower noise, better sensitivity, higher fill factors, very large arrays (5000×5000), higher spectrum range and higher speed transfer (1000 frames per second for a 1024×1024 CCD array). For instance, for InGaAs cameras prices should drop from \$25,000 to \$10,000 for a 128×128 focal plane array and concomitant performance should rise to 512×512 points. Extended wavelength (2.5 µm) InGaAs cameras—which do not require cryogenic cooling—should also become available soon.[6]

As shown in the literature, and in comparison with astronomy and medical applications, NIR imaging for food and agricultural applications is still emerging. The main reasons for this are the relative novelty of NIR in these areas and the lack of cheap cameras. These two obstacles have now almost been eliminated. We can consider that we have now reached, with NIR imaging, the point where visible imaging was in the seventies, i.e. the availability of linear cameras used for 2D imaging. It is obvious that NIR cameras will not undergo the same development that domestic video cameras have in the industrial market. NIR imaging will be a valuable aid in determining the composition of an object, especially when visible light is unable to bring a satisfactory answer for both macroscopic and microscopic applications.

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