Direct sight imaging spectrograph: a unique add-on component brings spectral imaging to industrial applications

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ABSTRACT

Imaging spectrometry has mainly been a research tool, employing laboratory spectrographs and scientific cameras. This paper describes an add-on imaging spectrograph that provides a unique combination of high quality image in a small, rugged, industrial, easy-to-use component. The spectrograph is based on a prism/grating/prism (PGP) dispersing element which provides straight optical axis, astigmatism free image and polarization independent throughput. A volume holographic transmission grating is used for high efficiency (up to 70%). The tubular optomechanical construction of the spectrograph is stable and small, D30 x L110 mm with F/2.8 numerical aperture and 2/3 inch image size.

Equipped with C-mounts, the spectrograph plugs between lens and area camera, converting the camera to a spectral line imaging system. The spectrograph allows the utilization of rapidly developing monochrome camera techniques, like high speed digital cameras, smart cameras and CMOS sensors, in color and spectral analytical applications. It is the first component available for upgrading existing industrial monochrome vision systems with color/spectral capability without the need to change the basic platform hardware and software. The spectrograph brings the accuracy of spectral colorimetry to industrial vision and overcomes the complex calibration that is needed when an RGB color camera is applied to colorimetric applications. Other applications include NIR imaging (up to 2500 nm), spectral microscopy, multichannel fiberoptics spectrometry and remote sensing.

Keywords: imaging spectrometry, spectral imaging, machine vision, imaging spectrograph, color, colorimetry, near infrared, CCD camera, InGaAs camera.

1. INTRODUCTION

Imaging spectrometry (spectral imaging) and its capabilities are quite seldom recognized by industrial vision system manufacturers and integrators, because current hardware has limited its use mainly to a research tool. Current techniques offer two basic approaches to imaging spectrometry. It is implemented either by acquiring a two dimensional image at different wavelengths at different times or a line image simultaneously at different wavelengths. The first approach is implemented by employing a rotating filter wheel or electrically scanned optical filter, like acousto-optic or liquid crystal filter, in front of a monochrome area camera. 2D imaging at a wavelength at a time suits to laboratory applications with a stationary sample. The latter approach is the right solution for a moving target (or instrument) and for a target varying quickly in time. Implementation requires an imaging spectrograph coupled to a monochrome area camera. One dimension of the camera (spatial axis) records the line pixels and the other dimension (spectral axis) the spectral information for each line pixel.

Most current imaging spectrographs employ a reflection grating and reflective optics that result in a folded optical path, making coupling to a system more complicated than it would be with a straight axis component (like a lens). Off axis configuration also causes astigmatism and other aberrations. Although they can be corrected to some extent either by using toroidal mirror optics or a holographically manufactured special reflection grating, a good image quality requires small

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aperture (f/4 or slower) and long focal length. These features, respectively, limit the light collection efficiency (throughput) and make the spectrograph construction large and bulky. The spectral throughput of mirror optics is dependent on polarization which becomes a severe problem in some applications.

These problems can be largely overcome with an axial transmissive spectrograph optics that is made possible by a holographically recorded transmission grating. It has been utilized in 90 degree (L-shaped) transmissive spectrographs[1]. This paper presents a unique straight axis (direct sight) imaging spectrograph. The straight axis configuration makes it as easy to couple to a vision system as a lens is. It almost totally eliminates polarization dependence that is still a problem with the L-shaped transmissive spectrograph. The direct sight spectrograph is based on a prism-grating-prism (PGP) dispersive element and transmissive optics. The PGP spectrograph technology was originally developed at VTT Electronics[2], one of the institutes of the Technical Research Centre of Finland, and is now commercially available from SPECIM as *ImSpector* imaging spectrograph products. They have been designed from first beginning to meet real industrial conditions.

For the first time this add-on spectrograph component brings the benefits of spectral imaging available in industrial vision systems. One of the most significant benefits is the improved colorimetric accuracy over RGB color camera. Also, other analytical applications, like quantitative determination of chemical constituents, that require precisely located spectral bands, become possible in vision systems. Currently the only possibilities to obtain spectral resolution in industrial line scan systems have been a single band filter in front of a monochrome camera and a three line camera equipped with RGB color filters[3] or a other set of spectral channels. The true color measuring capability of an RGB camera is quite limited. Its calibration to 'device-independent' color parameters, like X, Y, Z tristimulus values[4] and standard uniform color coordinates (like CIE L*a*b*)[4] requires a complicated procedure with known color samples. Still, with best calibration procedures the error goes up to 13 -14 ΔE_{ab}^* units in an 8 bit system[5,6] and to 8-9 ΔE_{ab}^* units with a 12 bit RGB camera[7], when a broad range of colors is to be measured. ΔE_{ab}^* is the distance between two colors in the three dimensional color space. Even a bigger problem with an RGB measurement in industrial conditions is, that its compensation for drift in light source color temperature (which usually occurs with aging and varying environmental conditions) also requires complex recalibration with a set of known color samples. Without compensation the error figures can increase to 16-18 and 11-13 ΔE_{ab}^* units, respectively[6,7]. These figures are well above the resolution of human eye that is from 2-3 ΔE_{ab}^* units with high density colors to below 1 ΔE_{ab}^* unit with light colors.

Spectral imaging brings here significant advantages, like the application of a spectrophotometer in single point laboratory colorimeters does. Color and color difference resolution below trained human eye performance is achieved. No other calibration is needed than one time spectral axis calibration in the beginning and a simple system response calibration with a white target. Light source color temperature drift is also compensated for on line with the use of white (or gray) reference target. Spectral measurement is free of metamerism (in an RGB system spectrally different colors can look similar). Another significant advantage of imaging spectrometry is the possibility to select by software the wavebands relevant to each application.

From another point of view, imaging spectrometry can offer advantages in industrial measuring systems by substituting a traversing single point sensor or a multiple sensor system with a single instrument. This means, in the first case, elimination of moving mechanics and better measuring coverage of the target, and in the second case, reduced cost and elimination of calibration mismatch between sensors.

2. DIRECT SIGHT IMAGING SPECTROGRAPH

2.1 Operating principle and construction

Schematic diagram of the straight axis PGP imaging spectrograph is shown in Fig.1. Light goes in through the input slit which defines the line geometry and spectral resolution of the system. The line image is dispersed by the PGP component to its continuous spectral distribution perpendicular to the line. The central wavelength of the design wavelength range goes straight through and shorter and longer wavelengths are dispersed symmetrically on both sides of the central wavelength. Placing a monochrome area detector at the image plane, it simultaneously records in one frame the line pixels and spectral distribution for each line pixel. Fig. 2 presents an example of a spectral line image across a target including different colors.

All the spectrograph components are assembled in a tube, making an extremely rugged and stable construction. The slit is lithographically manufactured on a metal coated glass substrate. Thus the spectrograph is fully sealed. The spectrograph tube size is only D30 x L110 mm for 2/3” (6.6 x 8.8 mm) image size. The spectrograph tube can be (equipped with standard mounts at the ends if needed) used as such for OEM purposes or in a C-mount housing that provides back focal length adjustment and rotational adjustment with respect to the housing (Fig. 1). For the user the spectrograph is like a lens which disperses a line image to spectral components.

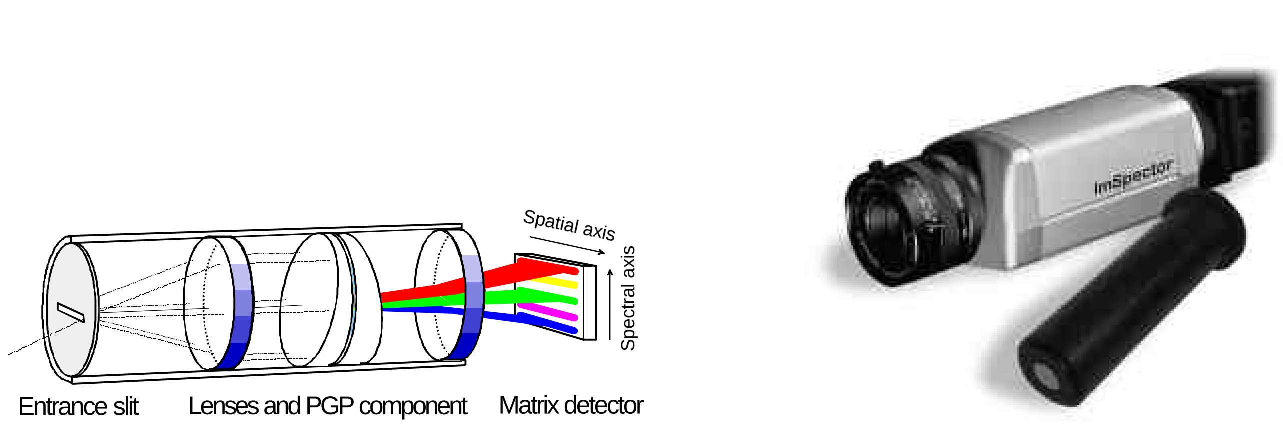

Figure 1. Schematic of the PGP direct sight spectrograph (left), and the basic spectrograph tube and a C-mount spectrograph coupled to a lens and camera (right).

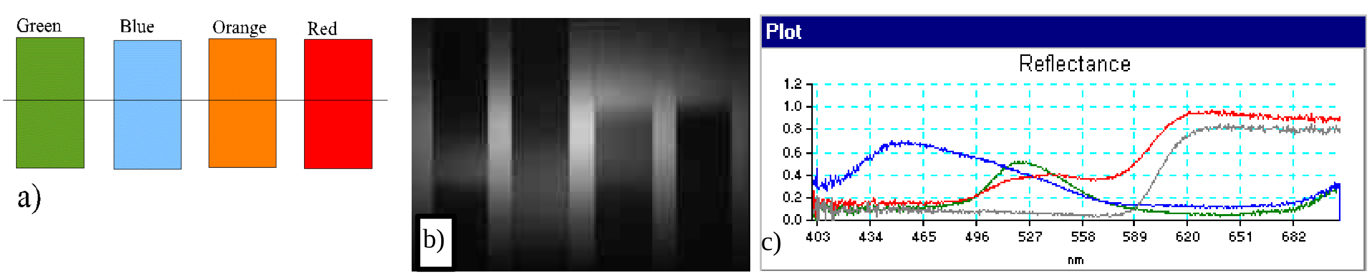

Figure 2. A target with green, blue, orange and red areas in white background (a), spectral line image across the target (b), and intensity profiles in spectral dimension of each of the color areas calculated according equation (2), showing reflectance spectrum of green, blue, orange and red (c).

2.2 Optical properties

The grating in the PGP component is a volume-phase transmission grating (holographically recorded in dichromated gelatin, DCG) that provides very high diffraction efficiency (DE) of up to 80-90% across a narrow range, but can also produce a good DE of 40-70% across a broad range, depending on design parameters. Fig. 3a shows two typical DE curves. The DE is practically independent of polarization (Fig. 3b) unlike in a reflection grating which typically shows polarization dependence of several tens per cent (Fig. 3c). This is a benefit in reflectance measurements.

Total spectral throughput is determined by the grating DE and transmission of other optical components. The latter is mainly determined in 400-2000 nm range by surface reflectance that can be reduced with a multi-layer anti-reflection (AR) coating to about 0.5 % in 400-700 nm and to 0.5-1 % in 400-1000 nm. Absolute transmission of the optics is about 0.85 x DE in 400-700 nm and 0.8 x DE in 400-1000 nm.

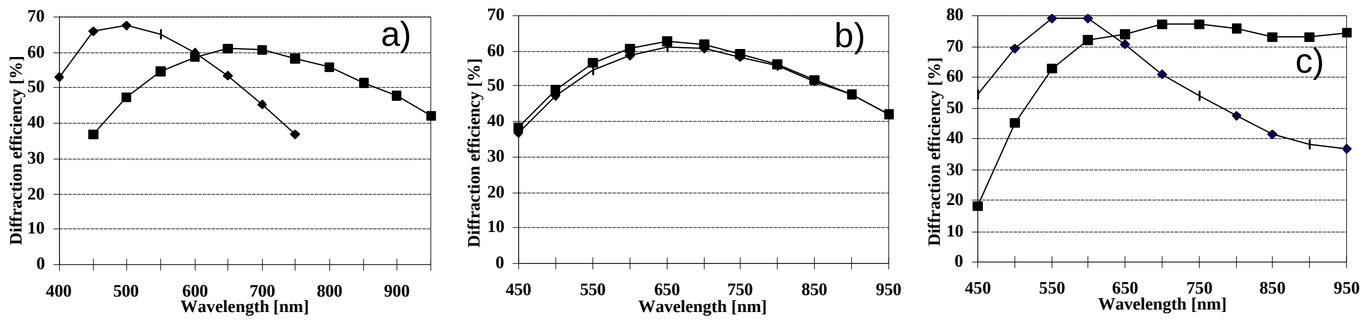

Figure 3. Typical diffraction efficiency of VIS (400-700 nm) and VIS-NIR (450-950 nm) volume-phase holographic transmission grating (a). Polarization dependence of volume-phase holographic grating (b) and reflection grating (c), shown for parallel and perpendicular polarization.

Direct sight transmissive optics produces a high quality image with short focal length, fast optics, thus minimizing the spectrograph size and providing good light collection efficiency. A standard PGP spectrograph for industrial applications is designed for f/2.8 aperture and 2/3" image (detector) size and uses 40 mm triplet lenses on both sides of the PGP. The image is practically astigmatism-free (spectral and spatial focal planes coincide in full image area) and thus eliminates one of the common problems of off-axis reflective spectrographs. Also, increase of magnification (keystoning) with wavelength from center wavelength at the edge areas is small. Error is < 2 μm in central 50%, < 4 μm in central 80% and < 10 μm in full image area. This corresponds to < 1 pixel error, respectively, with 11 micron pixel size. With these characteristics the optics produces almost uniform spot size, and thus uniform spatial and spectral resolution, in full image area. With 30 linepairs/mm lenses the optics limited spot size is 30 μm (half width).

The slit width affects both the spectral resolution and scene line width. Spectral resolution is linearly depending on the slit width down to a slit width of about 30 micron. Table 1 shows the optical resolution (defined as a half power band width) in three standard PGP spectrographs with four slit widths.

Table 1. Spectral resolution in standard PGP spectrographs.

	Spectral resolution / nm		
Slit / μm	400-710 nm 47 nm/mm	430 - 900 nm 71.2 nm/mm	850 - 1750nm 121 nm/mm
25	2	2.7	5
50	3.2	4.4	8
80	5	7	13
160	10	14	26

The scene line length (L_i) and width (W_i) are determined by the slit length (L_s) and width (W_s), lens focal length (f) and distance between target and lens (D):

$$L_i = L_s D/f, \text{ and} \quad (1a)$$
$$W_i = W_s D/f \quad (1b)$$

With a moving target, spatial resolution along movement is also affected by integration time per one scene line (= one detector frame) and speed of target.

Magnification of standard spectrograph optics is 1. Thus, the optical bandwidth determined by the slit covers on the detector a line area which has the same width as the slit. If increased scene line width is allowed, it is advantageous to use as wide a slit as the spectral resolution allows to minimize the required light power. Furthermore, the number of detector lines corresponding to the slit width can always be averaged (either by binning or software summing) without deteriorating the spectral resolution or increasing the scene line width.

3. SPECTRAL IMAGING SYSTEM

A spectral line imaging system consists of light source, imaging spectrograph, monochrome area camera and image acquisition and processing unit. Basically it is a standard monochrome frame acquisition system where the other frame dimension is interpreted as spectral data. However, several characteristics in the system components become differently important in a spectral imaging system than in a monochrome or RGB system.

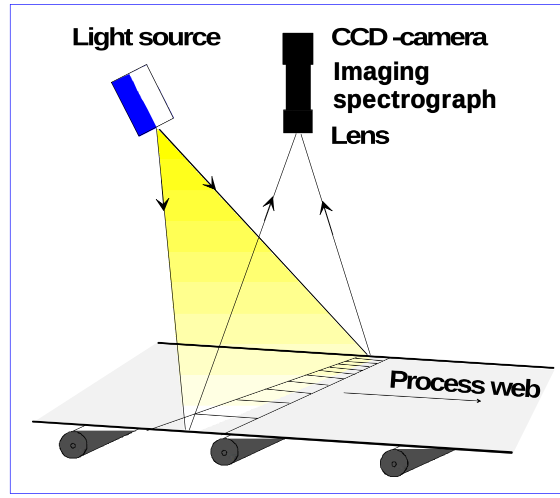

Figure 4. Schematic of spectral line imaging.

3.1 Illumination

Imaging spectrograph produces a new dimension of information by splitting light into its spectral components. This also means that higher total light power is needed than in B/W and RGB imaging. Minimization of light power is always a system benefit and careful consideration of optimized lighting solution is of importance in spectral imaging systems.

The amount of light required depends on:

- collection efficiency of lamp optics,
- camera sensitivity and S/N requirement of the application,
- spectral resolution,
- integration time,
- numerical aperture (f-number) of lens and spectrograph, and
- dimensions of the scene line to be imaged at a time.

Line lighting with uniform spatial distribution is the most efficient solution for every line scan system. Line lighting can be produced with e.g. fiber optic devices and a long filament tungsten halogen lamp together with a linear parabolic reflector or linear elliptical reflector and cylinder lens (glass rod). The latter is a low cost solution for high power requirements. Lighting should have flat and stable emission spectrum or, in fact, emission rising towards blue would be the optimum with most cameras. Emission peaks cause extra requirement for the dynamic range in a spectral system. Different lamps provide different features:

- Halogen lamps are stable and have a fairly long life time, but have weak blue emission. Spectral irradiance can be made more flat with a red attenuating filter (day light filter).
- Xenon produces a fairly flat visible spectrum, but is more unstable than halogen and requires a specific high voltage power source.
- Xenon flash offers a long life, high power light source for on line piece unit applications if 1-2% intensity and spectral variation from flash to flash can be tolerated (or measured in real time).
- Fluorescence, Hg and Ne lamps are <u>not</u> suitable light sources for spectral imaging.

3.2 Camera

Camera (and frame grabber) has a big role in what performance is achieved in an imaging spectrometer system. Camera characteristics to be considered against application requirements are its spectral response, sensitivity and linear dynamic range, speed and addressable lines.

As with lighting, a flat spectral camera response is ideal for spectral imaging. Unfortunately, most standard front-illuminated CCDs have a low blue response that limits achievable color measurement performance. CCDs optimized for visible region are increasingly becoming available in all price classes. The so-called virtual phase CCD offers inherently good response from blue to NIR. The best performance in full 400-1000 nm range is achieved with back-illuminated CCDs.

Good sensitivity and large linear dynamic range are important features in spectral imaging, because the amount of light tends to be small and small changes in spectral signals are to be detected. Here digital cameras offer best performance. Good linearity is significant in applications requiring absolute reflectance/transmittance information, like absolute color measurement.

Speed is an essential feature in on line applications. Imaging spectrometry produces a large amount of data when full spectral information is read out. This puts challenges both to readout implementation and data processing. Most applications however do not need full hyperspectral information, but a number of application specific bands. Thus, reading out only lines corresponding to these wavebands substantially reduces the amount of data and speeds up scan rate (up to more than 1000 spectral lines/s). Line addressable readout is achieved in CMOS, CID and diode array cameras. The only drawback for them to be ideal cameras for imaging spectrometry is (at least currently) their 10-50 times poorer sensitivity (higher noise level) than that of CCD.

3.3 Calibration and data processing

Data processing of spectral images depends largely on application. Many applications however require the following basic steps.

Calibration

a) Calibration of spectral axis by acquiring image(s) of known spectral lamp(s), like Hg, Ne, Ar and Kr.
b) Acquisition and storage of dark image by blocking the light entering the lens.
c) Acquisition and storage of image of white (or gray) reference target. For absolute reflectance data, a reference target with known spectral reflectance must be used. Spectralon is the best white reference material, but its high price limits its use mainly to research applications and to a tracing target. Ceramic or Teflon plate provide a good reference in many applications.
Steps b) and c) must be repeated time to time depending on lighting and camera stability with aging and temperature variations. Dark, white and later sample images must all be measured with the same system parameters (integration time, lens F-number, temperature,….).

Sample reflectance (transmittance)

Sample reflectance R is separated from the system response by taking, pixel by pixel, the ratio of each sample image to the white image:

$$R_{ci} = \frac{\text{sample}_{ci} - \text{dark}_{ci}}{\text{white}_{ci} - \text{dark}_{ci}} \tag{2}$$

This also compensates for

- offset due to CCD dark current,
- lighting spatial non-uniformity across the scene line, and
- light source color temperature drift.

Before reflectance calculation, it is useful to maximize signal-to-noise ratio by averaging (by binning or software) across as many rows as allowed without deteriorating the spectral resolution requirements. Usually at least the number of rows corresponding to the spectrograph slit width can be averaged. In a transmittance calculation, white measurement is substituted with a transmission measurement without a sample.

All the above steps are not required in every application. In case only relative color or other spectral variations are measured, there is typically no need for spectral axis calibration and calculation of sample reflectance, but data analysis can be done on dark current corrected raw data. There are several methods for spectral data processing and the selection of the most suitable one depends on application:

- Correlation of the spectral intensity profile to the profiles of calibration (teaching) samples suits for verification of a limited and pre-known set of samples/colors.
- Color coordinates can be calculated directly from spectral reflectance, without any other calibration with color samples as is needed with an RGB camera.
- Analysis of intensity ratios at predefined wavelengths or Principal Component Analysis (PCA) on limited or full spectral data suits to inspection/classification based on relative color differences and other relative spectral differences.

4. SPECTRAL IMAGING APPLICATIONS

4.1 2-dimensional colorimetry

Most laboratory single point colorimeters currently employ spectrophotometers. Spectral imaging offers basically direct compatibility to these instruments, with the benefit of simultaneous, contactless, pixel resolution measurement across a line. With a moving target (or instrument), a 2-dimensional color coordinate map of the target surface can be produced. Coordinate distributions and histograms can be used to verify surface color(s), detect color defects and classify the target.

The color determination accuracy of an imaging spectrometer depends on stability of lighting and measuring geometry (between reference measurements), accuracy of the white reference target, noise free dynamic range (in the weakest signal area, usually in blue) and quantization step. The performance of a 12-bit system was tested by measuring a set of 105 color samples in L*, a* and b* ranges of 23 - 94, –37 - 56 and –32 - 82 units, respectively. CIEL*a*b* values of the samples were determined with Minolta contacting laboratory colorimeter. The spectral imaging set-up consisted of halogen lighting (Solux 50W lamp with a filter attenuating yellow-red wavelengths by a factor of about 2.5), PGP imaging spectrograph (ImSpector V7 operating in 400-710 nm with 5 nm resolution), and front-illuminated 12-bit CCD camera. Illumination/measuring geometry was single sided 45°/0° and Spectralon was used as a white reference. Sample reflectances and L*a*b* values were processed from the spectral images by using SPECLab software (DV srl, Italy). 7 detector lines (corresponding to 5 nm resolution) were continuously averaged before L*a*b* calculation. The additional offset compensation described below was used.

Deviations from Minolta values were from 0.2-0.4 with light colors to 2-4 ΔE_{ab}^{*} units with high density colors, deviations being mainly due to error in b* value. Standard deviations from pixel to pixel in one sample were 0.1-0.4 units in L*, 0.1-0.5 units in a* and 0.2-1 units in b* . With a camera with a higher blue response the b-value behavior will be better and the above error figures smaller. Both absolute color and color difference measuring capability of spectral imaging is significantly better than with an RGB camera and is on the level and even below of trained human eye.

In order to achieve the best color measuring performance with a standard front-illuminated CCD that has a weak blue response, an additional offset correction may be needed. In an imaging system there are other small sources creating offset in the image than the CCD dark current. They are CCD frame shift smear and optical stray light. The offset due to these effects corresponds to the amount of light coming into the system. This offset can become significant in proportion to the weak blue signal and cause incorrectly high blue reflectance especially when measuring yellow/red colors. The offset level can be determined by using a long-pass filter to cut off incoming light across a small number of pixels in the beginning of each column (i.e. in the beginning of the wavelength range, see Fig. 6). Thus, ideally there should not be other than dark current generated signal at these pixels. The remaining signal after dark image subtraction is the offset due to the other factors. It can be compensated for by subtracting, column by column, the average value of the blocked pixels (avoffset) from all other pixels in the column:

$$R_{ci} = \frac{\text{sample}_{ci} - \text{dark}_{ci} - (\text{avoffset}_{\text{sample}})_c}{\text{white}_{ci} - \text{dark}_{ci} - (\text{avoffset}_{\text{white}})_c} \qquad [3]$$

The avoffset values must be calculated for the white image and each sample image separately. Choices for a blocking filter are e.g. Schott GG-420 and Hoya L-42 absorbing below 410nm, Kodak Wratten 2E absorbing below 415nm and UV blocking filters absorbing below 390nm (e.g. Schott GG-400).

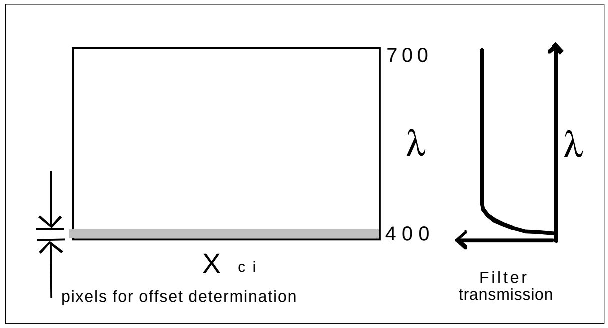

Figure 6. Schematic of long pass filter for offset compensation

4.2 Upgrade of monochrome vision systems

The direct sight spectrograph component provides a unique, simple and cost-effective method to add spectral resolution to an existing B/W vision system, and this takes place equally well with already installed systems (for e.g. shape or dimensional inspection) and with new installations. The existing B/W platform hardware and software can be utilised for data acquisition as well as in many cases for basic processing of the spectral image, like spectral profiling and correlation. Thus, although the colorimetric performance of the spectrograph would not be needed in a simple color recognition application, it will be in many cases more cost and time efficient to make use of the spectrograph than to modify the system for a RGB camera or to take to use a separate, parallel RGB system.

There is a large number of monochrome vision systems in dimensional and code reading applications in electronics, medical and other piece unit production and processing lines. Increasingly number of these applications need the addition of color identification of the piece units. A typical example is production of portable phones where both the cover color and display illumination color need to verified. Fig. 6 shows another example, on-line crate sorting, originally done by the shape of the bottles in the crate, is upgraded to identify also the bottle color. Color identification, at rate of 60 crates/min, is done by transmission measurement through the bottles in the crate.

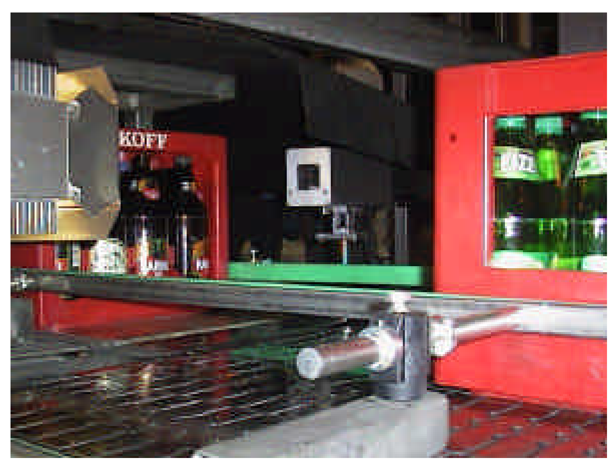

Figure 6. On-line crate sorting. Halogen light source on the left upper corner, *ImSpector* V7 and CCD camera looking from the square window on the center.

4.3 NIR imaging

Near infrared region (NIR, 700-2500 nm) contains spectral features that are related to absorption bands by several chemical compounds. They are currently widely used in single point laboratory and process analyzers in analytical chemical applications in agricultural and food, chemical, pulp and paper, and pharmaceutical industries. NIR absorption bands are strongly overlapped and thus a proper calibration requires usually a large number of precisely located measuring wavebands. The PGP spectrograph brings the potential to implement these analytical applications in vision systems. Standard silicon based cameras can be used up to 1000…1050 nm. Beyond that other detector materials are needed. InGaAs is the choice up to 1750 nm. Coverage up to 2500 nm requires a PtSi or InSb camera that, however, still are expensive for industrial applications.

The low NIR region up to 1050 nm contains valuable information about condition of living plants (in the spectral behavior of the so-called red edge in the reflection spectrum of green leaves), and ripeness of fruit (based on chlorophyll and sugar absorption bands). An example is given in Fig. 7. Tomatoes can be sorted according ripeness by combining color and NIR information. Same NIR feature appears in many fruit as well, like apples and kiwis. Also, the weak absorption bands of water and many organic compounds, like protein, cellulose oil/fat and hydrocarbons, in 900-1050 nm can be utilized in some applications. More precise quantitative analysis of these compounds requires the NIR range up to 1750 nm and in some cases even to 2400 nm. Applications include moisture profile determination (e.g. in paper), polymer identification in plastics sorting and plastics film thickness. Also, temperature profiles in metal and wafer processing become possible.

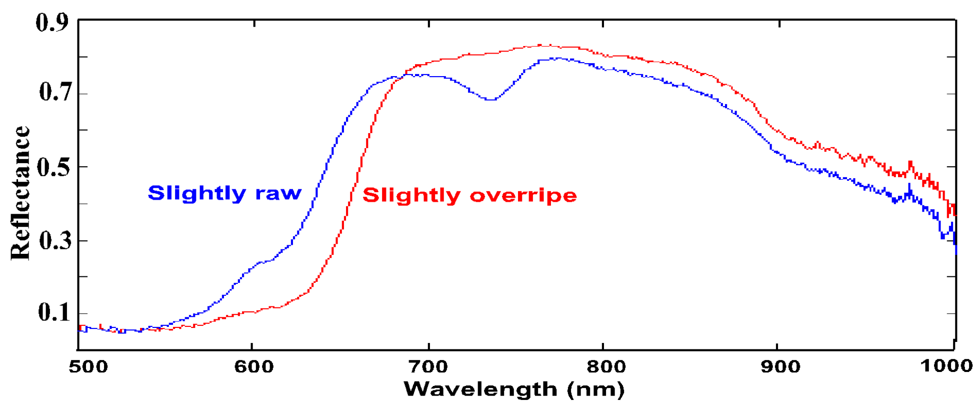

Figure 7. Spectral reflectance of tomatoes in 500-1000 nm.

Airborne and spaceborne remote sensing of agricultural fields, vegetation, waters (pollution, algae, corals), forests and minerals is an important application of spectral NIR imaging. The PGP spectrograph forms the heart of a new generation, small airborne imaging spectrometer operating in 400-1000 nm.[8]

4.4 Spectral microscopy

The direct sight imaging spectrograph is an ideal add-on component for microscopy. It fits directly to standard microscopes, adding spectral resolution to the system (Fig. 8). An x-scan table makes it possible to acquire a 2D spectral map of the target. A beamsplitter and another camera with a pattern generator can be added to monitor the target in a 2D monochrome image and show the user the spectral line position on the target.

Applications that benefit from spectral resolving capability include forensic investigations, cell biology, vegetation studies, fiber analysis and mineralogy and metallurgy. Fig. 8 shows a forensic application where inks of same color show different spectral response in the near infrared.

4.5 Multitrack fiberoptics spectrometry

An imaging spectrograph can be employed for implementing a robust multichannel spectrometer by coupling several fiber optic probes to the input slit. The good image quality of the PGP spectrograph allows to use up to 16 fibers of 200 micron simultaneously even with a 2/3" detector. This concept makes possible distributed on line and in line (with immersion probes) colorimetry and NIR analytical chemistry of webs, piece-units, liquids and slurries in food, chemical, paper, printing industries. Equipping the fiber probes with specific membranes will in the near future extent the range of applications to e.g.

blood (during surgery) and water analysis. As a single instrument, the multitrack spectrometer eliminates calibration and drift mismatch problems of multiple sensor systems.

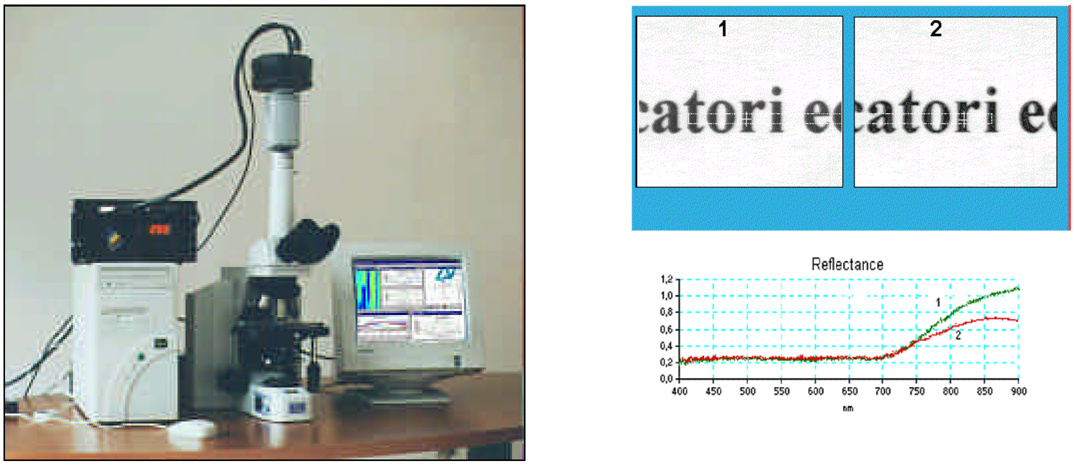

Figure 8. The direct sight spectrograph coupled to a standard microscope, and an example of ink recognition by spectral microscopy.

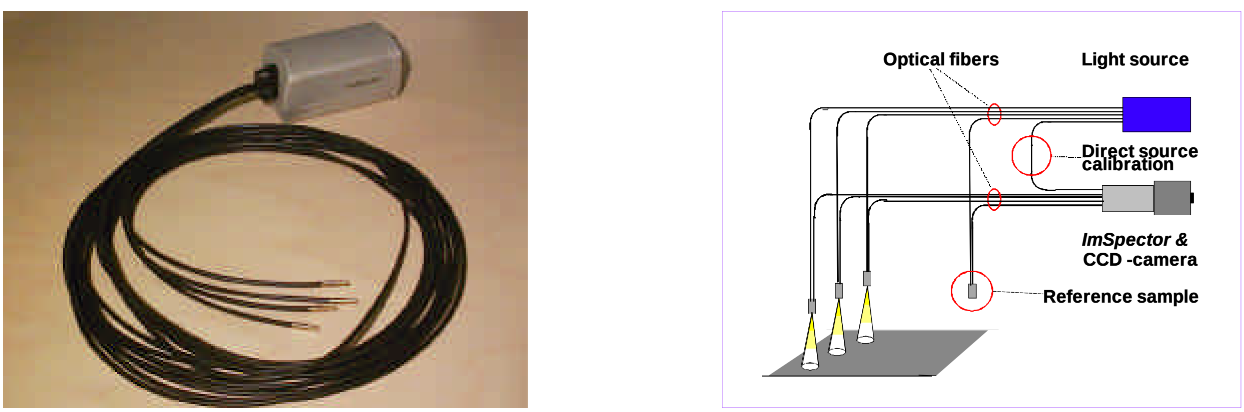

Figure 9. Standard PGP imaging spectrograph equipped with 4-legged fiberoptics, and schematic of a multitrack spectrometer.

5. SUMMARY

The direct sight PGP imaging spectrograph is a new add-on component that brings the benefits and possibilities of spectral imaging available in industrial vision. Many applications, like colorimetry and chemical analyses, that are currently done in single point or with traversing or multiple sensors, become possible in pixel resolution and distributed with a single instrument.

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