

SmartSpectra: Applying multispectral imaging to industrial environments

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Abstract

SmartSpectra is a smart multispectral system for industrial, environmental, and commercial applications where the use of spectral information beyond the visible range is needed. The SmartSpectra system provides six spectral bands in the range 400–1000 nm. The bands are configurable in terms of central wavelength and bandwidth by using electronic tunable filters. SmartSpectra consists of a multispectral sensor and the software that controls the system and simplifies the acquisition process. A first prototype called Autonomous Tunable Filter System is already available. This paper describes the SmartSpectra system, demonstrates its performance in the estimation of chlorophyll in plant leaves, and discusses its implications in real-time applications.

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1. Introduction

In certain application fields where image processing is involved, the use of spectral information in the visible (VIS) and near-infrared (NIR) range is critical. For example, vegetation characteristics such as fractional vegetation cover, wet biomass, leaf area index, or chlorophyll content can be easily estimated from a set of multispectral reflectance measures [1,2]. In the fruit processing industry, the VIS range is necessary to detect defects on the skin. However, two key parameters for the ripeness of a fruit, the total soluble solids and the skin chlorophyll, are better measured in the NIR domain [3], since NIR energy is absorbed by certain chemical groups and not by others.

Systems for spectral measuring can be classified according to their spectral resolution or their spatial resolution. Narrowband hyperspectral systems are usually based on point spectrometers or linear spectrometers. These systems can measure many precise narrow spectral bands of a point light source or a line source, in the VIS and NIR ranges and beyond. On the other hand, Red, Green and Blue (RGB) cameras provide a very high 2-D spatial resolution while the spectral information is badly separated into three overlapping bands in the VIS range. Some systems can acquire narrowband spectral information with high 2-D spatial resolution, but at the cost of a very long acquisition time [4].

SmartSpectra¹ is a smart multispectral system that fits somewhere between these two approaches. The SmartSpectra camera provides six bands with fully configurable

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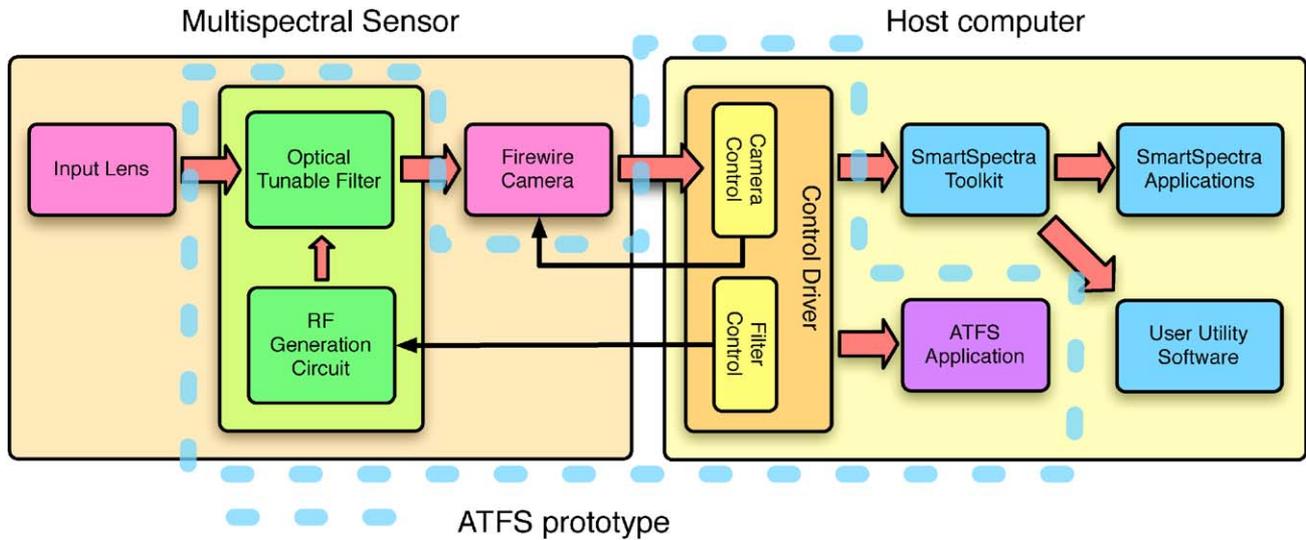


Fig. 1. A block scheme diagram of the SmartSpectra system and ATFS.

spectral shape from snapshot to snapshot, in the range 400–1000 nm. Each band can be as narrow as 5 nm or as wide as an RGB band. At the same time, the limited number of bands reduces the acquisition time of the system yet maintaining the relevant spectral information. The small number of bands also reduces the subsequent processing time, encouraging the use of the system in real-time applications. As a variety of classification and quantification problems demonstrate, six bands is a good trade-off between resolving power and response time of the system [5,6].

For some applications, each band can be configured to acquire a linear combination of narrowbands. This functionality is useful in order to estimate convenient parameters such as the optimum multiple narrowband reflectance (OMNR) index [1] with a single SmartSpectra band.

The SmartSpectra camera acts like a RGB camera in terms of spatial resolution and integration time. Furthermore, the flexibility of band configuration allows the system to adapt to a wide variety of problems and changing situations in real-time.

SmartSpectra technology is affordable while assuring robustness. The system is intended to make multispectral techniques accessible to industrial, environmental, and commercial applications. Although the system is not fully operative yet, a first prototype called autonomous tunable filter system (ATFS) is finished and functional.

The system can be divided into two main blocks, the sensor and the host computer, as depicted in Fig. 1. The sensor part mainly involves optics and electronics, while

the host computer comprises the driver for sensor configuration and image acquisition, image processing software, and the development of specific algorithms for the application fields of fruit quality assessment, agriculture, and environmental monitoring. The camera acquires six bands that may be located in the VIS and NIR spectra, and simulates two common Firewire RGB cameras. The ATFS prototype is a reduced version of the SmartSpectra system that uses an off-the-shelf Firewire camera and does not include the Toolkit software.

This paper is presented as follows. The state of the art for multispectral devices is reviewed in Section 2. Section 3 presents a complete description of the system, followed by a description of the host software. Section 4 describes the performance of the system for a demonstrative application and analyses the real-time implications of the system. The paper ends with the conclusions and a bibliography.

2. State of the art

The SmartSpectra system uses state-of-the-art technologies in the fields of multispectral analysis, tunable filtering, and light sensing. We will now describe them with some detail.

2.1. Multispectral devices

The SmartSpectra system is different from other spectral systems on the market. The most similar devices available are spectrometers. These devices are used to analyse the spectrum of a point, a line or a bi-dimensional image. As a result, the user gets a plot (1-D data), a matrix (2-D data) or a hypercube (3-D data),

(footnote continued)

(Fifth Framework). More information about the project can be found on the website: <http://www.smartspectra.com>.

respectively, that represent the source in the spectral domain.

Point spectrometers are based on the spectral dispersion of a light beam using a reflection grating or prism. The spectrum is projected onto a linear array of sensors (CCD or photodiodes). Each element of the array is exposed to a single wavelength of light. The combination of the array elements responses forms the spectrum of the beam. The 1-D output data of these systems represents the radiance value for each wavelength. There are many commercially available point spectrometers, presenting very different resolutions, spectral ranges and prices. For example, AvaSpec-256 from Avantes BV (www.avantes.com) gives 256-point spectrum measures in the visible range, while Fieldspec Pro from Analytical Spectral Devices Inc. (www.asdi.com) provides 1250 spectral bands in the 350–2500 nm range.

Linear spectrometers analyse a linear image by dispersing the light into a rectangular area that is projected to a 2-D array sensor. The output of these systems is a 2-D data matrix representing spatial information in one dimension and spectral information in the other. *Inspector* spectrograph from Spectral Imaging Ltd. (Specim; www.specim.fi) is a highly successful system very suited to conveyor belt applications. *PARISS spectrometer*, from LightForm Inc. (www.lightforminc.com) is a complete linear spectrograph system designed to be coupled to a microscope.

Finally, multiband systems can capture 2-D spectral images by the use of a spectral filter in front of a 2-D sensor array. The band selection can be performed by the use of a wheel of filters or by the use of a single tunable filter. There are two main types of electronically tunable filters: acousto-optic tunable filters (AOTF), and liquid crystal tunable filters (LCTF).

A commercial multispectral system based on LCTF is available from Opto-Knowledge Systems Inc. (www.ok-si.com). The system is formed by a VIS or NIR LCTF

coupled to a standard C-mount camera, and the control and acquisition software.

AOTFs are solid state devices that act as electronically tunable spectral bandpass filters. An AOTF consists of a properly oriented birefringent uniaxial crystal to which a piezoelectric transducer is bonded [7]. The application of a radio frequency (RF) signal to the transducer produces an acoustic wave that propagates inside the crystal. The travelling acoustic wave modulates the refraction index of the material periodically, due to the elasto-optic effect. The process acts like a volume phase grating, leading to the diffraction of a particular wavelength that satisfies a specific momentum-matching condition inside the birefringent medium. The wavelength filtered by the crystal can be rapidly tuned across a wide spectral range by changing the applied RF signal. The acousto-optic interaction also changes the polarization state of a single wavelength. The structure of an anisotropic uniaxial medium permits two normal modes (ordinary and extraordinary) to propagate in any direction with mutually orthogonal polarizations and different velocities. If the AOTF input light beam at the tuned wavelength is extraordinarily polarized, then it emerges from the AOTF ordinarily polarized, and vice versa.

The acousto-optic filter design uses two basic geometric configurations, collinear and non-collinear. In the non-collinear configuration [8], depicted in Fig. 2, the directions of the optical and acoustic waves are different, causing diffracted and non-diffracted rays to be angularly separated at the filter output.

Although AOTF technology is not new in imaging systems for the scientific community [9], there are no commercial systems available. Romier [10] has developed an imaging spectrometer for remote sensing applications. Wachman [11,12] has successfully used an AOTF for hyperspectral ultra-high-resolution microscopy. Other scientists have reported the use of AOTFs

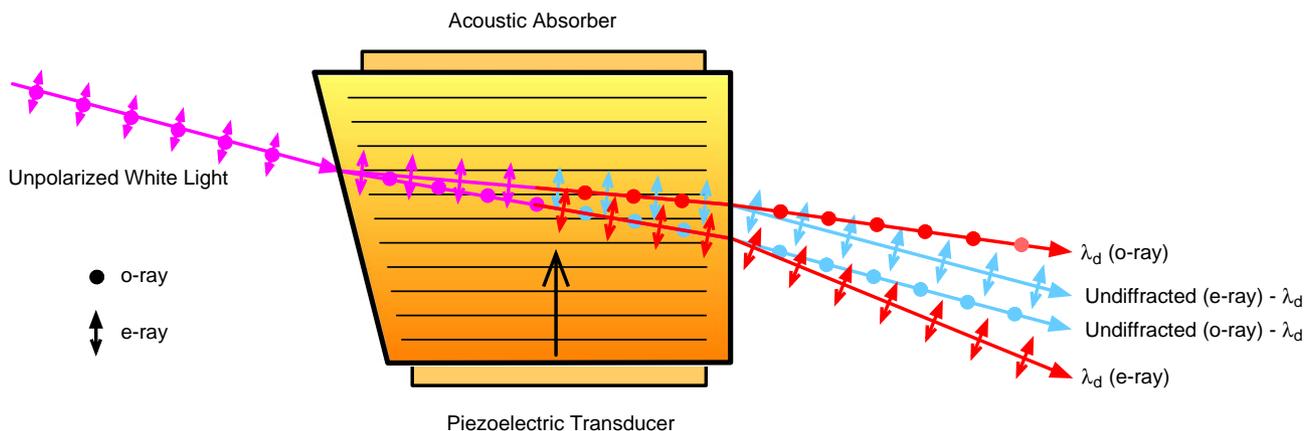


Fig. 2. Non-collinear AOTF design. The zero-order (undiffracted) and first-order (diffracted) outputs are separated by a certain angle.

in hyperspectral imaging systems in the NIR and VIS ranges for astronomical observations [13–15].

2.2. Imaging sensors

The SmartSpectra camera uses a commercial 2-D sensor array. Three different sensor technologies can be applied to the system.

Charge-coupled devices (CCD) were invented in 1969 [16] and have become a common choice for scientific and high-quality applications. Around the same time, the complementary metal-oxide semiconductor (CMOS) sensor was discovered [17], but it was not until early 1990s that the commercial production of these sensors was feasible and gained the high-volume market (see [18] for a complete historical review). Intensifying technologies have been specifically considered since they can boost the responsivity of the sensor, and the SmartSpectra applications can be very demanding since narrow bandwidths severely reduce incident light.

2.2.1. CCD

CCDs are composed of a matrix of photogates on which the light is collected [19]. The photons are converted into electrons (charge) and transferred to the output. At the output stage charge is converted to voltage. The bandwidth of the output limits the reading speed of the sensor. Conventional CCD sensors have a single output, but some CCD sensors have 2, 4 or even 32 outputs. A conventional CCD can read as many as 30 full images per second (for 640×480 sensor elements). A high-speed CCD with 32 outputs can read 300 full images per second. Multiple outputs may decrease the uniformity of the image, because of the differences among the output stages.

CCD characteristics greatly depend on the field of application [20]. Applications in astronomy and science demand the highest performance, such as very low noise and high responsivity. The reduction of the readout noise is achieved with long time exposure and low readout speed. To increase the responsivity, CCDs for astronomy are normally back-thinned. Alternatively, CCDs for science have a large full-well capacity, allowing for 14 or 16 bits output digitalization. CCDs for astronomy and science use Full Frame architecture, which is the slowest but most sensitive architecture. The main manufacturers of high-performance CCDs are E2V Technologies (e2vtechnologies.com), Scientific Imaging Technologies, Inc. (SiTe; www.site-inc.com) and Fairchild Imaging (www.fairchildimaging.com).

By contrast, industrial applications demand lower spatial resolutions and responsivity but higher data rates. CCD sensors for machine vision do not demand resolutions higher than 10 bits, while the required spatial resolution is very dependent on the application. Normally sensitivity is not an issue since lighting can

be controlled. Dalsa (www.dalsa.com), PerkinElmer (optoelectronics.perkinelmer.com), and Hamamatsu (www.hamamatsu.com) are some manufacturers of industrial CCDs.

2.2.2. CMOS

CMOS sensors are formed by a matrix of photodiodes. Unlike CCD sensors, each photodiode is connected to a charge-to-voltage converter next to it. Therefore, the charge is not read sequentially at the sensor output, but in parallel inside each sensor element. Consequently, the readout speed can be much higher than in a CCD but the uniformity is much lower. CMOS sensors use the same manufacturing technology as other CMOS integrated circuits and are accordingly cheaper to produce than CCDs.

There are two main groups of CMOS sensors depending on the application. We can find low cost CMOS for cost-sensitive applications and high performance CMOS for high-speed imaging. Eastman Kodak (www.kodak.com), Micron (www.micron.com), Dalsa (www.dalsa.com), Photonfocus AG (www.photonfocus.com) and FillFactory (www.fillfactory.com) are examples of high performance CMOS manufacturers.

2.3. Intensified technologies

Intensified technologies are used to boost the CCD responsivity in low light level conditions. The main technologies are: intensified CCD (ICCD), electron-bombarded CCD (EBCCD) and low light level CCD (L3CCD).

The ICCD uses an intensifier tube to increase the number of photons that hit the CCD by several orders of magnitude. The intensifier tube contains an electron multiplier and a phosphorescent output screen. Therefore, ICCDs can perform a wavelength shifting if the spectral response of the multiplier differs from the emitting wavelength of the phosphorus screen.

The EBCCD is a hybrid of the intensified and the conventional CCD. In this device, photons are detected by a photocathode similar to that in an image intensifier. However, the released electrons are accelerated across a gap and impact directly on the back side of a back-thinned CCD instead of a phosphorus screen. These energetic electrons generate multiple charges in the CCD resulting in a modest gain of a few hundred.

Currently, a new technology called L3CCD can surpass the performance of the other intensified technologies. L3CCD technology improves the performance of conventional CCDs by inserting an on-chip multiplication stage prior to the output conversion. This stage increases the signal gain while the noise is not amplified. L3CCD technology resembles an image intensifier implemented in solid state. At present two companies manufacture this kind of sensor: E2V

(e2vtechnologies.com) and Texas Instruments (www.ti.com). E2V is the only manufacturer to provide back-thinned L3CCD.

The conclusion is that the current market provides a range of solutions for a multispectral system. As concerned to filtering technologies, AOTF provide a sensible solution for vision applications and have the potentiality to become a low-cost, robust technology in the near future. Regarding the imaging sensors CMOS-based sensors match the requirements of many real problems at a lower cost and simplicity than CCD counterparts so they have been preferred for the development of the first prototypes of our system. Intensified technologies are an emerging market with breakthrough products being launched every few months with significant price reductions. These latter technologies can be the optimum choice in certain demanding applications but may not be in main stream products.

3. Description of the system

The SmartSpectra system is divided into two blocks, the multispectral sensor and the software that runs in the host computer (Fig. 1).

3.1. Multispectral sensor

The SmartSpectra system acquires multispectral images by means of an optical tunable filter in front of a monochrome camera. The tunable filter is configured to select which light wavelengths reach the sensor. The selected spectral region can be a single passband with a bandwidth between 5 and 100 nm or a linear combination of up to four passbands summing a total bandwidth of up to 100 nm.

The selected filter technology is the AOTF, which diffracts a wavelength of the incoming light by means of an acoustic wave in the RF range. The frequency, power, and spectral distribution of the RF signal define the intensity and bandwidth of the diffracted light [21].

When a pure sinusoidal RF signal is applied to the AOTF, the crystal diffracts a single wavelength with a very narrow bandwidth. The diffraction efficiency is directly proportional to the RF power. Moreover, if a linear combination of pure sinusoids is applied to the crystal, the corresponding combination of wavelengths is diffracted [22]. This characteristic can be used to increase the bandwidth of the filtered passband (by using a set of very close sine signals) [11] or to generate a complex comb-shaped output (by using a set of separate sinusoids) [23].

The first prototype of the SmartSpectra optical tunable filter used this multi-sine approach to excite the AOTF, implemented as a custom RF driver design

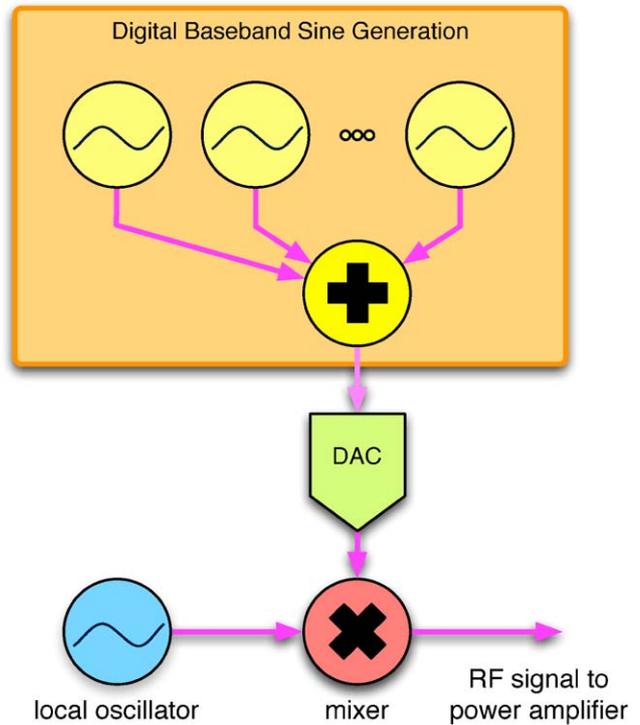


Fig. 3. Multi-sine AOTF driver.

[24]. The concept of this RF driver is shown in Fig. 3. A DSP is used to generate a multi-sine signal in baseband, which is up-converted to the proper frequency range with an RF mixer circuit. This driver was tested on a Brimrose AOTF showing a moderate performance. The response was not very good because the mixer added some intermodulation products to the RF signal. These products spread the power density and therefore reduced the diffraction efficiency in the selected band and increased the out-of-band diffracted light.

Another approach takes advantage of the fast dynamic response of the acousto-optic devices and the fast switching capabilities of modern digital direct synthesizers (DDS). This technique drives the AOTF with a sweeping acoustic frequency, i.e., the frequency applied to the crystal varies cyclically from an initial frequency to a final frequency in constant steps. By taking an integration time that is a multiple of the complete sweeping time, the acquired image is proportional to the intensity of the spectral range diffracted by the different frequencies.

A new RF driver was developed using this approach. Fig. 4 shows the block diagram of the driver, which was implemented in the ATFS prototype. The core of the driver is the AD9858, a 1 GigaSample per second DDS, capable of generating a frequency-agile analogue output sine wave at up to 400 MHz. The DDS is clocked by a 1 GHz signal generated by the AD4360-2 integrated synthesizer and voltage-controlled oscillator. Both

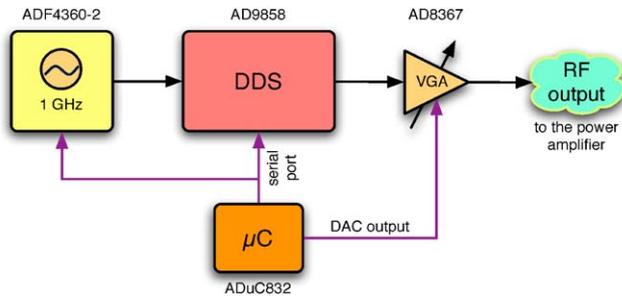


Fig. 4. Block diagram of the sweeping frequency driver.

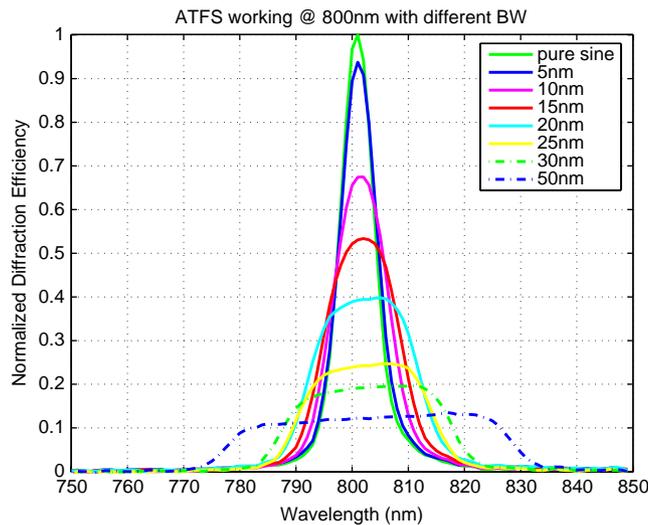


Fig. 5. Diffraction efficiency of the sweeping frequency driver.

integrated circuits are controlled by an ADuC842 Micro-Converter. The RF signal amplitude is controlled by an AD8367 variable gain amplifier. All integrated circuits are from Analog Devices Inc. (ADI; www.analog.com). The low-level RF signal output is amplified by the AP5300-2 power amplifier from RFPA (www.rfpa.com).

The DDS has been programmed to generate a complete sweep within a 5 ms period. The initial and final frequencies are calculated in real-time from the bandwidth requirements, as well as the frequency step. Fig. 5 and Table 1 show the performance of the system, measured over the Brimrose AOTF. The figure shows the diffraction efficiency (DE) of the system when the RF generator was configured to filter a passband centred at 800 nm with a variable bandwidth. Although the DE decreases as the bandwidth increases, the total energy contained in the passband is kept almost constant, i.e., the efficiency of the system is not altered.

The DDS can be switched instantly among four frequency profiles. This feature allows the generation of an arbitrary four-sine signal in which each sine is used

Table 1
Measured performance for the sweeping frequency driver

Selected bandwidth	Peak DE (normalized)	Passband energy (arbitrary units)	Real bandwidth (nm)
Pure sine	1	5.6979	7
5 nm	0.9375	5.5079	7
10 nm	0.6748	6.6571	12
15 nm	0.5336	6.7626	15
20 nm	0.3980	7.2320	21
25 nm	0.2470	5.2832	24
30 nm	0.1968	5.4018	31
50 nm	0.1350	5.8306	50

The peak DE has been normalized to the pure sine DE. The real bandwidth is the measured full width at half maximum value (FWHM). The passband energy is the integral of the DE on the FWHM area.

one-fourth of the time. For an integration time that is multiple of the signal period, the result is equivalent to the multi-sine approach with four sines.

3.1.1. Autonomous tunable filter system (ATFS)

The ATFS is a finished prototype of the SmartSpectra with complete multispectral capabilities. It is composed by the following hardware components (see Fig. 1):

Input lens: The function of this lens is to focus the object inside the optical tunable filter. Although the system accepts any C-mount optic lens, the selected lens was the telecentric TEC-M55 objective from Computer (www.cbccamerica.com/cctvprod/computar). Telecentric lenses have shown to be the best choice for AOTF imaging systems because they reduce chromatic aberration and stray light [25].

Optical tunable filter: The optical filter of the ATFS is a CVA-100-0.4-1 AOTF with video adapter from Brimrose Corp. (www.brimrose.com). This AOTF presents a wide working range of 400–1000 nm, due to the use of two transducers optimized for different frequencies. The crossover wavelength is 580 nm (which corresponds to a 130 MHz acoustic frequency). The RF output is switched from one transducer to the other, depending on the selected range.

RF generation circuit: The AOTF is excited by the abovementioned sweeping frequency generator. The acoustic frequency range is 218–130 MHz for one transducer and 130–70 MHz for the other.

Firewire camera: The ATFS uses a commercial Firewire camera to acquire the multispectral images. The software driver on the host computer synchronises the camera trigger with the RF generation circuit, and is responsible for the image data flow from the camera to the upper software layers. Currently, this driver supports different models of Firewire cameras. In the ATFS prototype a high performance CCD

camera was used, the Retiga EX IEEE 1394 monochrome camera from QImaging (www.qimaging.com), providing 1360×1036 pixel images with 12-bit resolution.

Two photographs of the ATFS prototype can be seen in Fig. 6. The system is controlled through a Windows-based application.

3.2. Host software

The SmartSpectra host computer software presents three main blocks (see Fig. 1). The first is the driver that controls the multispectral sensor and manages data acquisition, the second is the toolkit that provides the hyperspectral possibilities of the system to the end user,

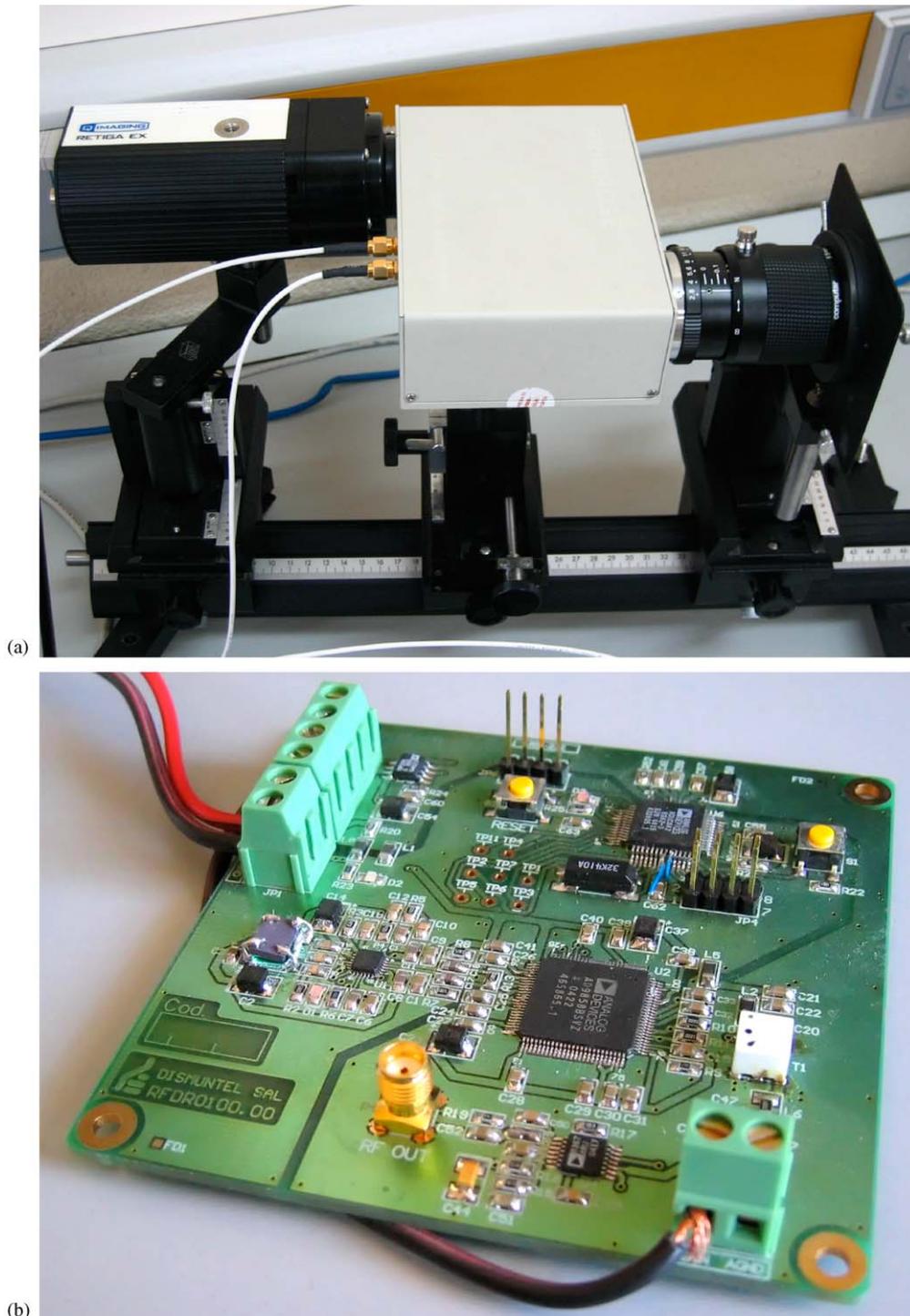


Fig. 6. Pictures of the ATFS prototype: (a) optical filter with the input lens and the camera; (b) RF generator.

and finally the User Utility software. The ATFS prototype uses the same low-level driver as the SmartSpectra system, but it does not require neither the toolkit or the User Utility software.

3.2.1. Driver for camera and filter control

The control driver provides an API that is to be used in the Windows environment by high-level software.

The driver for sensor control of the SmartSpectra multispectral sensor is a set of low-level functions that allow the toolkit in the host computer to communicate with the sensor configuration port and set up all its functionalities. This driver is used for both the ATFS prototype and the SmartSpectra toolkit.

The driver of the camera is divided into two parts, one is used to configure and perform the image acquisition, while the other is used to configure the filter. The synchronization between the RF generation and the camera acquisition is guaranteed by using this driver.

The driver uses the IEEE-1394 (Firewire) digital bus to communicate with the camera and the RS-232 or

USB bus to communicate with the optical filter. The driver supports any camera adhered to the 1394-based Digital camera (D-Cam) specification suggested by the Camera Working Group of the 1394 Trade Association, whose purpose is to guarantee interoperability for this class of devices. The D-Cam specification defines a set of registers, fields within those registers, video formats, modes of operation, and controls for each one. The driver has also support for the QImaging and Photonic Science cameras (based on L3CCD). The driver sends configuration parameters to the camera through the Firewire bus, starts and stops imaging acquisition, and manages the images transferred from the camera.

The filter control block is responsible for sending the filter parameters to the RF generator (initial and final RF frequencies, frequency step, number of steps, and RF power). These parameters are calculated by the driver from the wavelength and bandwidth specified by the upper software layer.

The driver for sensor control acts as an interface between the SmartSpectra toolkit and the multispectral

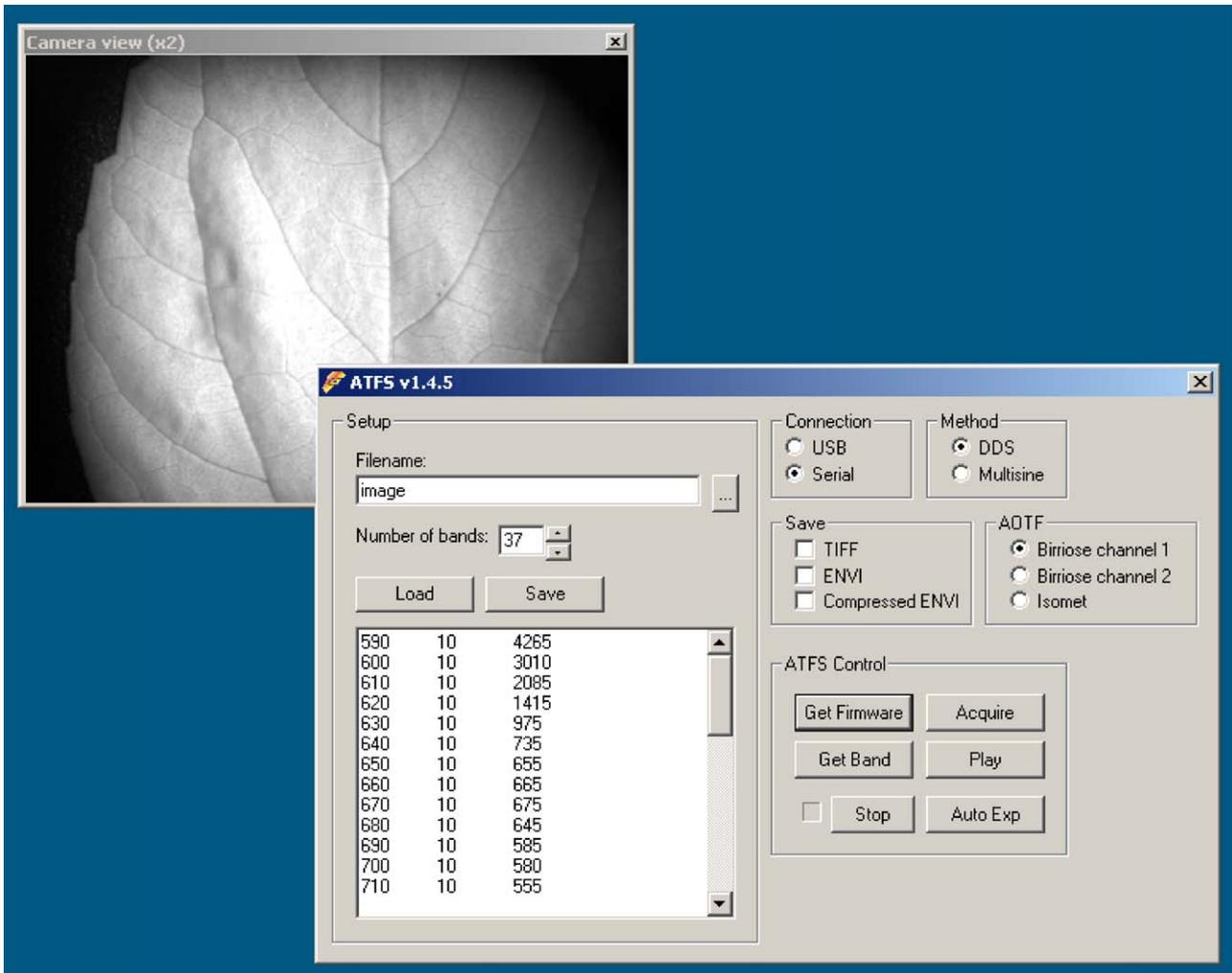


Fig. 7. ATFS application running on a PC. The camera view shows a sunflower leaf in the 840 nm band.

sensor. Given any acquisition request, the driver implements the camera configuration, the filter configuration and a synchronized acquisition when the filter is ready.

3.2.2. ATFS application

The ATFS application provides a graphical user interface (GUI) to the sensor driver. This application allows the user to easily acquire multispectral images. Fig. 7 shows a screenshot of the application.

The user must specify a list of bands to acquire, with their central wavelengths, desired bandwidths and, optionally, integration times. If no integration time is provided, the ATFS application performs a smart auto-exposure procedure that estimates the best integration time for each band in order to maximize the dynamic range. Once the bands have been specified, the system sequentially takes the images for each band configuration and saves the whole set of images as an ENVI² hyperspectral file or as multiple TIFF files.

The application is prepared to save images of a Spectralon® target in a different ENVI file as a white reference. In addition, it can measure the dark current of the system (by switching off the AOTF) and save it as a dark reference ENVI file. These two sets of images can be used in ENVI in order to accurately calculate the reflectance of the images, with the following equation (expressed here for the n th band):

$$\text{Reflectance}_n(\%) = \frac{\text{Image}_n - \text{DarkCurrent}_n}{\text{WhiteReference}_n - \text{DarkCurrent}_n}.$$

3.2.3. Toolkit

The Toolkit is the high-level software layer to be used by the system integrators for accessing and programming the sensor. The main purpose of this software layer is to provide basic data structures and processing tools of the multispectral images to extract useful information. The rationale of the toolkit is that system integrators and developers only need the basic tools to interface the low-level layer of the system.

Therefore, the main features of the toolkit are oriented to provide programming tools to achieve the above-mentioned connection of the system with the application integrator, and it focuses on the specific functionalities related with the features of the system, rather than providing general-purpose image processing techniques. The features of the currently developed toolkit, which is available via the web page of

the project (www.smartspectra.com), can be summarized as follows:

- It allows using an object oriented programming language, C++, widely used for application development in image analysis and machine vision.
- The user may easily extend the set of functions and abstract data types defined in the toolkit.
- The toolkit works on PC-based architectures under the most common operating systems: MS-Windows and Linux.
- The toolkit provides high-level functions to access to low-level drivers for sensor configuration, acquisition, etc. It also provides basic functionality for image representation and access, storage and other common multispectral image manipulation functions.
- There also exist novel specific functions for multispectral image processing developed during the project like:
 - Filtering and segmentation techniques for multispectral images using several bands.
 - Statistical analysis of multispectral data, allowing automatic band selection using feature selection techniques and dimensionality reduction of data representation.
 - Invariance image representation of multispectral data, including several types of invariant representations available in the literature and the ones developed.

The toolkit also includes the possibility of interfacing image file in the ENVI format, in order to simplify access to system developers and integrators that use this software tool.

3.2.4. User Utility software

The User Utility software is a software application that provides potential users with a quick insight into the technical features of the SmartSpectra camera in an easy and effective way. This software application uses a graphical environment to display all the information extracted from acquired images (using the SmartSpectra camera), stored images (using the most extended graphic file formats) or the result of processing images using the available functions in the toolkit.

Therefore, the features of the present developed the User Utility software include:

- Inquiries to find the SmartSpectra cameras present on the IEEE 1394 bus and select them.
- Display and configuration of the SmartSpectra sensor parameters.
- Set acquisition mode and image acquisition format.
- Display acquired or stored multispectral images, showing particular multispectral features (pseudo-RGB

²ENVI is an image processing package from Research Systems Inc. (www.rsinc.com). It is widely used for spectral image analysis by the remote sensing community.

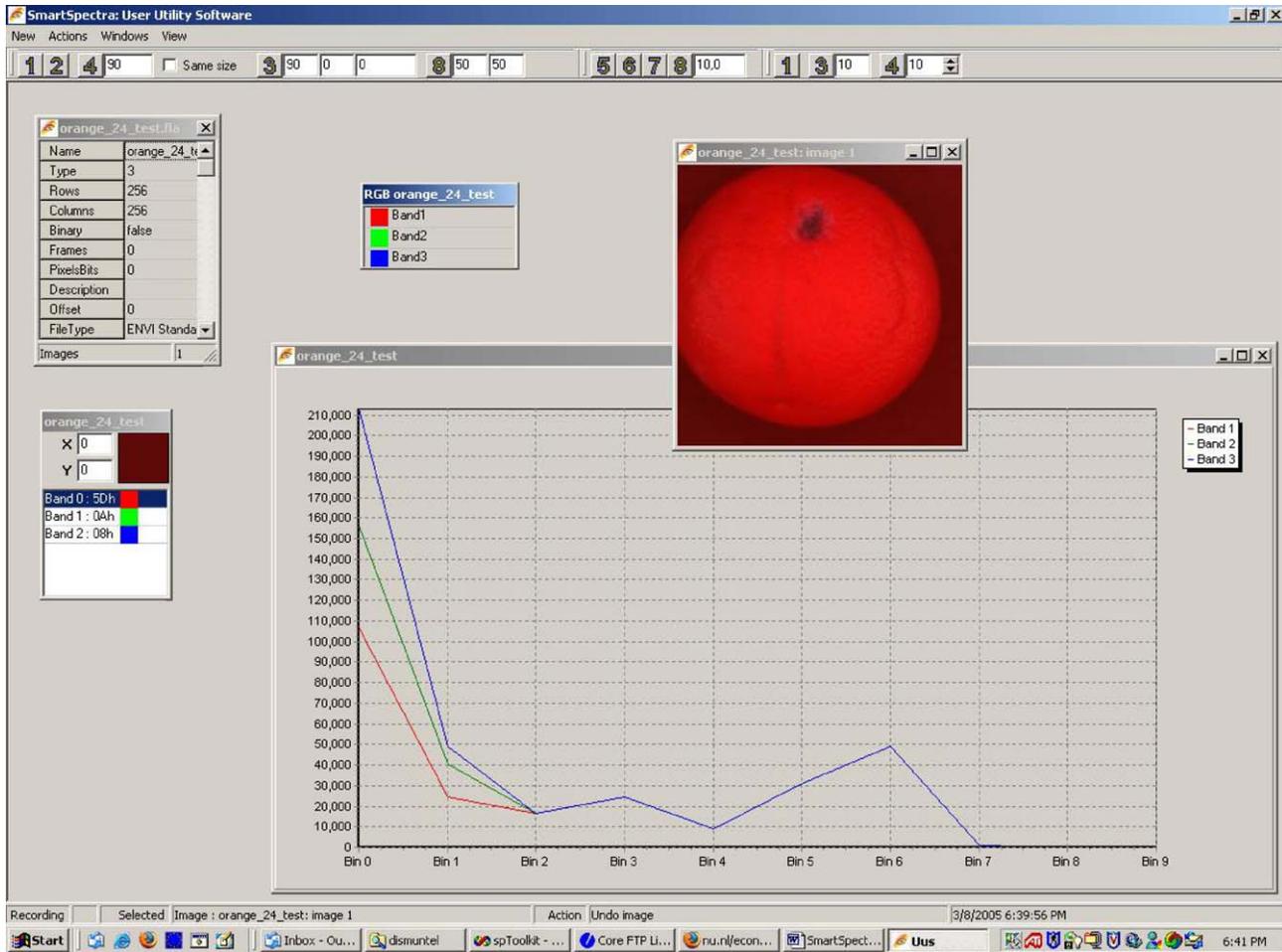


Fig. 8. User Utility software running on a PC.

composition of three bands, spectral distribution of a pixel, etc).

- It allows to perform in a friendly environment most of the image processing functions available in the toolkit, including the specific multispectral processing data like band selection, multispectral invariant representations, etc.

The SmartSpectra User Utility software runs in MS-Windows environment. Fig. 8 shows a screenshot of the application.

4. Performance and real time implications

The performance of the ATFS prototype has been evaluated in the estimation of chlorophyll content in plant leaves. This is a quantitative problem, with controlled lighting and no time constrains. Nevertheless, the system can perform well in complex real-time problems, as discussed in this section.

4.1. Chlorophyll estimation

Traditional methods of pigment analysis require selection of samples and extraction of their chlorophyll content through ‘wet’ methods and spectrophotometric analysis, with consequent destruction of the leaf. The analysis of leaf reflectance is a method for estimating biophysical parameters as well as providing important information about the plant status in a fast and non-destructive way. The SmartSpectra system provides spectral and spatial information simultaneously, and allows regular repetition of the measurements in order to detect variations in the plant status as a whole.

In the last few years, many studies [26–29] have proven the relationship between spectral reflectance and pigment contents in leaves. In 2004, Maire presented an exhaustive compilation [30] of all indices published from 1973 to 2002. We have selected the one proposed by Blackburn [31] that calculates a normalized difference vegetation index, $NDVI = (R_{800} - R_{680}) / (R_{800} + R_{680})$.

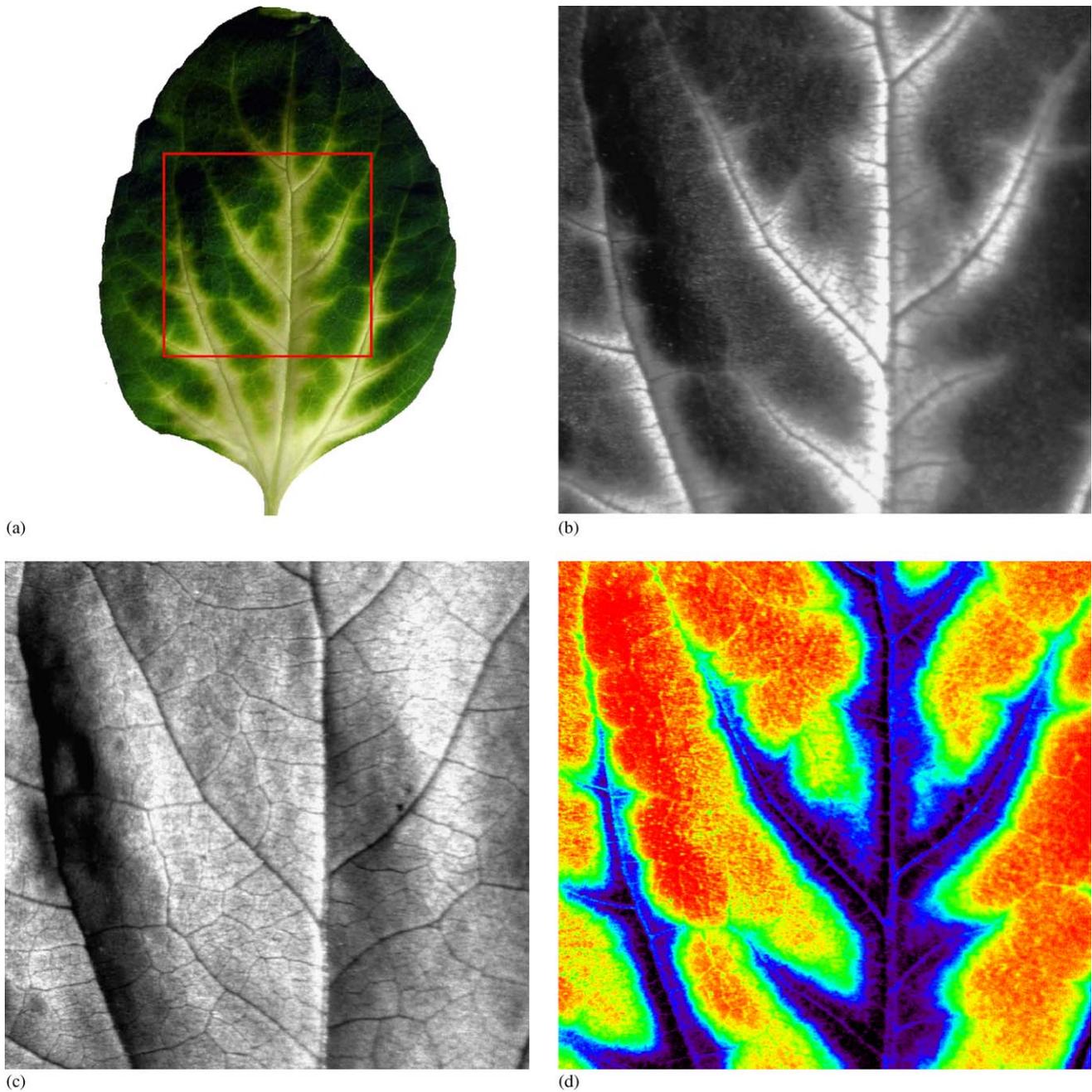


Fig. 9. Study of the chlorophyll content of a sunflower leaf treated with herbicide. (a) RGB image of the leaf, where the red rectangle represents the selected study area. (b) Reflectance of the leaf in the 680 nm band. (c) Reflectance of the leaf in the 800 nm band. (d) Image of the chlorophyll distribution calculated with the $NDVI_{800,680}$ index. The figure is shown in false colour (rainbow) so that details can be clearly visualized. The blue colour corresponds to the lowest concentration and red to the highest.

Fig. 9 shows the application of this index to the multispectral image of a sunflower (*Helianthus annuus*) leaf. The leaf was treated with herbicide and thus presented high variations in chlorophyll content. Fig. 9(a) represents a colour image of the leaf showing the damage caused by the herbicide in the areas surrounding the veins. Fig. 9(b) shows the image of the leaf in the 680 nm band, while Fig. 9(c) shows the 800 nm band. Finally, Fig. 9(d) shows the chlorophyll distribution

calculated with the index. A lower chlorophyll concentration was observed close to the central nerve, where the herbicide effect was clearly stronger.

4.2. Real-time implications

Contrary to other multispectral systems, the Smart-Spectra system is more suitable for real-time applications since it acquires a small amount of bands with

fast and flexible band configuration. The six spectral bands provided by the system are enough for most applications.

Although theoretically, for a classification-oriented application, the more bands, the better the classification rate, the improvement in the classification rate is not significant from a certain number of bands due to the *curse of dimensionality* [32]. When adding more bands, the amount of information grows considerably, while the classification rate remains almost constant. In addition, in hyperspectral imaging, most of the information present in contiguous bands is redundant, since they tend to be highly correlated. Some studies show that a reduced number of spectral bands, around six, is enough to characterize most of the classification tasks [5].

Nevertheless, the system can use less than six bands when not required by the application, reducing further the acquisition and processing time. For example, in the estimation of chlorophyll content (Section 4.1), only two bands are needed. Therefore, the system could be configured to acquire only these two bands.

Another advantage of the SmartSpectra system with respect to colour RGB images or any usual trichromatic representation is that the calculation of spectral invariants is more feasible. The fact of having narrowband representations allows calculating invariants with simple operations like subtracting and dividing band values of a pixel, speeding up further image processing steps [33,34]. Therefore, many image processing tasks become easier and computationally efficient when invariant representations to illuminant intensity, illuminant, colour, shades, highlights, etc. can be obtained, improving the computational performance, for instance, of image segmentation and object recognition processes, and contributing to meet real time constraints in some demanding applications.

Spectral invariance has been demonstrated in the context of fruit quality assessment. An invariant representation to illumination intensity and highlights has been developed [33] to overcome these common problems in visual inspection of fruits. Multispectral segmentation algorithms have been developed taking advantage of invariant representation and using information about multispectral borders [35]. Classification schemes based on neural network classifiers and techniques to deal with large volumes of multispectral data are the core of the classification process to recognize the different external defect parameters [36].

Regarding hardware aspects, the synchronization between the RF generator and the digital camera allows a fast multispectral acquisition. The total acquisition time is the summing of the sensor configuration and settling time, the camera integration time and the image

readout and transfer time. The response time of the AOTF when switching on the acoustic frequency in the SmartSpectra RF generator is smaller than 5 ms. Likewise, the readout of the digital camera takes less than 70 ms and the image transmission about 56 ms (for the Retiga EX camera). Those times can be normally neglected when compared to the integration time, in the range 200 ms–2 s for the Retiga camera with indoor illumination.

5. Future work

The SmartSpectra system is an extended version of the ATFS prototype. The authors are currently completing this system, which includes a proprietary Firewire camera and a software toolkit, neither of which are covered by the ATFS (see Fig. 1). Moreover, the SmartSpectra system will include some improvements over the ATFS hardware.

SmartSpectra camera: The SmartSpectra system will include a Firewire camera specifically developed for the system and based on the IBIS5 CMOS sensor from FillFactory (www.fillfactory.com). This camera will take full advantage of the optical filter. The camera and RF generator will share the same controller in order to configure the correct gain and integration time for each band, and maintain perfect synchronization.

SmartSpectra toolkit: The SmartSpectra toolkit has already been developed, but it has been tested only on the ATFS hardware. Some tests and minor corrections will be necessary for the final SmartSpectra system.

SmartSpectra hardware: The experience gained during development of the ATFS prototype has led to some improvements on the final SmartSpectra system. Two different AOTFs covering the VIS and NIR parts of the spectrum will be used, instead of one AOTF with two transducers, as the Brimrose AOTF has shown very bad performance in one transducer region. The selected AOTFs are custom made designs from Gooch and Housego, UK (www.goochandhousego.com).

The RF generator will include an integrated 1 W power amplifier and a RF power control loop.

Another AOTF excitation technique is also being investigated, based on the use of a very high-speed digital to analog converter (DAC) circuit. This circuit, the AD9726 from Analog Devices Inc. (www.analog.com), will allow the generation of a multi-sine RF signal in the proper frequency range without the need of an up-converting circuitry. This technique overcomes the drawbacks of the baseband multi-sine generator while retaining all of its benefits. As the different RF frequencies will be applied simultaneously to the AOTF instead of sequentially (DDS driver), a great reduction of the integration times is expected.

6. Conclusions

The SmartSpectra system proposes a new concept for multispectral imaging. It is a hybrid of common colour cameras (three broad overlapping bands) and spectrometers (many very narrow bands). It uses six bands that are configurable in central wavelength and bandwidth from snapshot to snapshot. Stress is placed on robustness, flexibility, and affordable cost in order to make it accessible to final users. A software platform is built to simplify the use of this camera. The use of a reduced number of quickly configurable bands makes the system especially suited for real-time applications.

The authors have developed the hardware for the first prototype using a commercial digital camera. This prototype has been used successfully for the estimation of the chlorophyll content on plant leaves. Real-time implications of the system have been analysed throughout the paper.

A final version of the system is being completed at the time of writing. Some third parties have been identified in order to share images or access the platform.

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