Hyperspectral camera application for remote gas analysis

S M Neverov
Scientific and Technological Center of Unique Instrumentation of the Russian Academy of Sciences, 117342, Moscow, Butlerov Street, 15
E-mail: snev85@yandex.ru

Abstract. The report reviewed current systems for monitoring gas leaks at industrial facilities. Since in industrial plants the emission of some gases can be technologically justified, and the presence of others indicates a violation of the technological process and is a sign of an emergency situation, a possible option is described not only for detection the fact of leakage, but also for the classification of detected gases. We considered existing hardware-software complexes including acousto-optical, and listed their shortcomings, such as insufficient sensitivity and low data processing speed. In general, we describe the novel technical implementation of imaging spectrometry. For simultaneous detection of spatial and spectral properties of objects, the infrared sensor is divided into a mosaic of the smallest optical filters. Each filter passes individual intervals of the spectrum, blocking the others. The uncooled detector 640×512 can be covered with 16 filters, which spectral characteristics should correlate with the absorption spectra of target gases.

1. Introduction
In recent years, hyperspectral cameras have become widespread in the food industry to assess food safety. The advent of cost-effective production allowed compact, lightweight and low-cost hyperspectral systems to become part of machine vision systems for food sorting and quality control in the pharmaceutical industry. Such applications require cameras to “see” targets on the conveyor and to ignore other background information. People are currently successfully solving this task, but the transition to automated systems eliminates the human factor and saves costs in the long term. The technology of machine vision using hyperspectral camera is more productive and faster than a human, and can see far beyond the visible spectral region, resolving damages inaccessible to the human eye.

Understanding of hyperspectral imaging principal and technical advantages and disadvantages of different source and detectors are important for obtaining reliable hyperspectral images with high quality. The choice of instrument components, their adjustment and calibration procedures require a good understanding of the hyperspectral imaging principles. The spectral imaging system creates a stack of images of the same object in different spectral wavelength ranges. There are three main classes (figure 1) in the field of spectral imaging: multiband, multispectral, and hyperspectral (ultraspectral). The main difference is the number of images inside the spectral cube and their bandwidth. Multiband devices provide detection in several rather wide bands (figure 1). Multispectral instruments area characterized by narrow channels usually of the same bandwidth. Hyperspectral systems detects the spectral range with no gaps. The last provide usually hundreds or thousands of images that make each pixel of a hyperspectral image have its own continuous spectrum. The result is
a hyperspectral image, which is a three-dimensional (3D) Hyperspectral Cube. It consists of pixel vectors and contains the spectral information as well as two-dimensional spatial information [1].

As for the data acquisition modes, they are divided into four: spot scanning (or whiskbroom), line scanning (or pushbroom) scanning, spectral scanning and single shot (figure 2). While the whiskbroom mode gets all the bands, pixel by pixel, by moving the detector in the $x$-$y$ space to store the data in array form pixel by pixel recording of spectral channels, this method called band-interleaved-by-pixel (BIP), a pushbroom mode works similarly, but instead of a pixel scanning a spatial line is formed, which, ultimately, is written to the array line by line recording simultaneously all the spectral bands, this type called band-interleaved-by-line (BIL) cube. Several other features of pushbroom mode include compact size, light weight, easier control and higher signal level due to use of small differential gratings as the spectral element. In flat scan mode, a per-channel recording array create spectral bands sequential (BSQ) cube, consisting of several images taken consequently, each of which contains spectral data relative to the entire $x$-$y$ space. Finally, there is a mode that receives all spatial and spectral data at the same time, known as a single shot. It uses a multispectral detector. In addition, we indicate some of the problems of each mode. Whiskbroom is a slow-motion mode, and pushbroom should be used for a short time to avoid the risk of inconsistencies in the spectral band level (saturation or underexposure). Flat scanning is hardly suitable for moving environments, while single shot is a technology under development that still does not support high spatial resolution. [1]
2. Element base
Below are analysis of the features of devices on various elemental base.

2.1. Sources
Light sources generate light to illumination of the target and are an internal part of optical control systems. Typical light sources used in hyperspectral imaging systems are: halogen lamps, light emitting diodes, lasers and tunable light sources.

- Halogen lamps. The main halogen lamps disadvantages are relatively short service life, high heat capacity, the thermal shift of the spectral peak due to the change of temperature, unstable power due to fluctuations of the operating voltage and sensitivity to vibration.
- Light emitting diodes (LEDs). Critical disadvantages of LEDs include sensitivity to large voltage fluctuations and transition temperature, low light intensity compared to halogen lamps and obtaining granular light when several LEDs are used together.
- Lasers. Light generated by lasers has a higher intensity and much narrower bandwidth than LEDs. However, in the spectral range from 8 µm to 14 µm lasers have big power consumption, dimensions and weight.
- Tunable light sources. This source is ineffective for point and line scanning, but is well-suited for BSQ mode. That is why, tunable light sources are practically unsuitable for conveyor systems.

For our application sources are not needed, as a detection distance must be close to 50 meters and system will be used like handheld device with small size and weight. For remote sensing, the natural radiation sources should be used like the Sun or thermal radiation of the environment (in MIR range).

2.2. Spectral elements and detection devices
Devices with wavelength dispersion are necessary for hyperspectral imaging systems using broadband light sources. They have the function of dispersing a broadband light into different wavelengths. Typical examples listed below: filter wheels, imaging spectrometers, acousto-optic tunable filters, liquid crystal tunable filters, Fourier-transform (FT) imaging spectrometers, and single-image devices.

- Filter wheels. Main disadvantages of filter wheels are mechanical vibration from moving parts, slow wavelength switching and unmatched image due to filter movement.
- Imaging spectrometers. They normally operate in linear scanning mode, have the ability to instantly disperse incident broadband light at different wavelengths and generate a spectrum for each point on the scanned line without the use of moving parts. The main disadvantages of reflective gratings are great difficulties with distortion correction.
- Tunable filters. Acousto-optic tunable filter (AOTF) and liquid crystal tunable filter (LCTF) are electronically tunable bandpass filters. On base of acousto-optic interactions in the crystal, AOTF selects light at one wavelength from a broadband source due to periodicity of applied acoustic field. The liquid crystal tunable filter (LCTF) has electronically controlled liquid crystal cells inserted between two parallel polarizers to transmit light with a certain wavelength, while the light outside the bandwidth is eliminated. Disadvantages of the tunable filter are small light acquisition angle and low efficiency of light collection, the need for linearly polarized incident light, which can cause 50% light loss, and a longer exposure time than that of spectrometers working with images in similar lighting conditions.
- Fourier-transform Image formation spectrometers. FT imaging spectrometers use an interferometer for the self-interference of broadband light, resulting in an interferogram that contains its spectral data. The generated interferogram is then computed using the inverse Fourier transform to resolve the composition of the optical frequencies (inverse wavelengths) of broadband light. However, spectrometer requires a time interval to shift the moving mirror, so it takes a long time to collect the interferogram to obtain accurate spectral resolution.
- Single-shot devices. Single-frame images can simultaneously collect multiplexed spatial and spectral data, providing a hypercube at a video frame rate. It should to say, single-frame scanners are still at an early stage.
- Zonal detectors. Zonal detectors have the function of quantifying the intensity of the light received by converting incident photons into electrons. Cameras used charge coupled devices (CCD) and metal-
oxide-semiconductor structures (CMOS) are the two main types of solid-state detectors. Photodiodes made of light-sensitive materials are the main element of CCD and CMOS to convert radiation energy into an electrical signal. The main disadvantages of CCD are that both the photodetector and the reading amplifier at each pixel are not included in the CCD image sensor, as a result its need time to receive an image. The limitation of CMOS cameras is higher noise and dark current than in CCD, due to the built-in chips used to transmit and amplify signals, and as a result lower dynamic range and sensitivity than the CCD [2].

For the developed single-shot system we choose a microbolometer as a small and light detector. Infrared radiation with a wavelength of 7.5 to 14 microns falls on the detector material, heating it and thus changing its electrical resistance. This resistance change is measured and processed as temperatures that can be used to create the image. Main advantages of microbolometer camera: low power consumption relative to cooled detector thermal imagers, very long mean time between failures, less expensive compared to cameras based on cooled detectors. Also it provides real video output immediately after power on, and for applications that require relatively short distances, the physical dimensions of the camera are even smaller. It disadvantage is less sensitive than cooled thermal imagers and photon detectors (due to higher noise), but sensitivity of microbolometers rise every year.

The hyperspectral camera creates a cube of data with a size of about 100 or more narrow spectral bands in each pixel, in the instantaneous field of view [4]. The number of pixels varies depending on the sensor tool. A typical GC system collects light (usually reflected from a topographic object) that passes through a slit, spectrally decomposed using a grid or prism and focuses on a detector or sensor. For each pixel or raster cell, the system receives and graphs the brightness value at each wavelength, thereby creating a continuous spectrum for the image cell. Scientists can compare these high-resolution spectra over the entire wavelength region with standard spectral libraries for identification. For example, concrete versus granite, healthy cultures compared with diseased cultures, healthy cells compared with cancers, and even determine the cause of human redness (from stress or not) (figure 3) [5].

![Hyperspectral image slice](image.png)

**Figure 3.** Hyperspectral image slice.
3. The system developed
A hyperspectral camera measures adjacent spectral bands, in contrast to multispectral imaging, which measures diversity spectral bands. This difference favorably distinguishes multispectral cameras for our task, since no cumbersome computation and costly operating systems are needed for unfolding the spectrum study.

The advantage of a multispectral camera is that its infrared sensor is divided into a mosaic of the smallest optical filters. Each filter passes individual infrared regions of the spectrum, blocking the others. On the figure 5 below you can see graphs with absorption lines from 8 µm to 14 µm (spectral range that we choose for detection) of gases that is critical to indicate on the Oil & Gas facilities. We choose 8 gases: Propane \( \text{C}_3\text{H}_8 \), Butane \( \text{C}_4\text{H}_{10} \), Methane \( \text{CH}_4 \), Ethan \( \text{C}_2\text{H}_6 \), Acetylene \( \text{C}_2\text{H}_2 \), Carbon monoxide \( \text{CO} \), carbon dioxide \( \text{CO}_2 \), Ammonia \( \text{NH}_3 \), Hydrogen sulfide \( \text{H}_2\text{S} \). We identified the strongest absorption lines, which are at the same time placed at a distance from each other (that is important item to avoid overlapping). Second critical point – all this lines are out of water absorption areas.

The uncooled detector 640 × 512 allows setting up to 16 filters, the spectral characteristics of which are selected after analyzing the absorption spectra of several gases. The presence of these gases at an industrial facility is associated with continuous monitoring of the concentration of these gases in the working area of the enterprise. To obtain the desired configuration was processed data array. In the future, based on the images obtained using the software included in the system, it will be possible to calculate the gas concentration and select the gas type in the image with the corresponding color in real time. Technically we placed very narrow optical filter on each channel (16 channels), we use duplication, so one gas – 2 channels. We calculate small lenses that must glue on the infrared detector together with filters. Usually in multispectral cameras use the turret of optical filters to receive on one detector a few spectral image, but huge disadvantages of this scheme is a time between images. For example to receive image in 10 spectral range takes around 10 seconds (based on Telops and Bertin multispectral cameras specification [6, 7]). This time is more than enough to lose position of the gas cloud – as a result each images takes in different environment condition. In our innovation scheme we receive image in wide spectral range between 8 µm and 14 µm less than one second.

The development of methods for the simultaneous analysis of a significant amount of gases can be simulated using acousto-optic tunable IR spectrometers [8], which allows one to tune in series to an

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**Figure 4.** Critical gases absorption lines from 8 µm until 14 µm spectral range.
arbitrary set of wavelengths. Finding optimal combinations of spectral lines and bands requires solving optimization problems [9] and can be modeled on a similar spectrometer that implements the function of controlling the width of the transmission window of an acousto-optic filter [10].

4. Conclusion
We have analyzed the optical and spectral characteristics of hyperspectral and multispectral cameras, revealed their distinctive features and principles of construction, and determined the trends of their design. As a result of the research, we identified an important problem: the absence of technical solutions that meet the full set of requirements for multispectral cameras and methods for industrial monitoring. We suggest a novel group of multispectral cameras for industrial use at hazardous production facilities. We plan to provide detection of multispectral image in wide spectral range 8 – 14 µm instantly (less than 1 second). Each of the 16 channels will provide information regarding critical gas components and its concentration.

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