Review Article

Helge Bürsing* and Wolfgang Gross*

Hyperspectral imaging: future applications in security systems

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Abstract: The idea behind hyperspectral imagers (HSI) is to generate an image with hundreds of contiguous narrow channels, the so-called spectral bands. As each material has a specific spectral signature, robust detection and classification of specific materials is now achievable. Spectra can be characterized by narrow features in their signatures that broadband and multispectral cameras cannot resolve. As a result of technical progress, new HSI with higher spatial resolution and better signal-to-noise ratios have been developed. Additionally, it is possible to buy small HSI that weigh less than 1 kg, which opens up new applications in surveillance and monitoring with unmanned aerial systems (UAS). Despite the capabilities of hyperspectral data evaluation, HSI is applied to surprisingly few tasks. This is a result of the sheer amount of recorded data that needs to be analyzed and the complex data pre-processing when the sensors are not used in a controlled environment. Also, extensive research is required to find the most efficient solution for a given task. The goal of this letter is to introduce and compare the different sensor techniques, discuss potential use for applications in civil security and give an outlook of future challenges.

Keywords: civil security; disaster management; hyperspectral imager; remote sensing.

1 Introduction

The idea behind hyperspectral imagers (HSI) is to generate an image with hundreds of contiguous narrow channels, the so-called spectral bands. As each material has a specific spectral signature, robust detection and classification of specific materials are now achievable. Spectra can be characterized by narrow features in their signatures that broadband and multispectral cameras cannot resolve. As a result of technical progress, new HSI with higher spatial resolution and better signal-to-noise ratios have been developed. Additionally, it is possible to buy small HSI that weigh less than 1 kg, which opens up new applications in surveillance and monitoring with unmanned aerial systems (UAS). Despite the capabilities of hyperspectral data evaluation, HSI is applied to surprisingly few tasks. This is a result of the sheer amount of recorded data that needs to be analyzed and the complex data pre-processing when the sensors are not used in a controlled environment. Also, extensive research is required to find the most efficient solution for a given task.

Today HSI is already used for applications in remote sensing, e.g. land cover classification [1], vegetation analysis [2], and disaster management and monitoring [3] and also for mineralogy [4], food processing [5], and sorting of bulk materials.

The purpose of this paper is to give an overview of the possibilities and an outlook of what might be possible in future security systems. The next chapter gives a brief overview of commonly used techniques for hyperspectral data recording. The basics of each data acquisition method are explained, and their advantages and disadvantages are discussed. Additionally, this paper introduces the fundamental ideas of hyperspectral data exploitation and analysis. Current research in relation to applications in security systems are shown in chapter 3, whereas the final chapter gives an outlook on possible future applications.

2 Technology

The underlying technology of HSI is, in one form or another, common practice in optronics. The goal is to record an image of a given object or scene with full spectral

***Corresponding authors: Helge Bürsing and Wolfgang Gross,** Fraunhofer-Institut für Optronik, Systemtechnik und Bildauswertung, Standort Ettlingen, Scene Analysis, Ettlingen, Germany, e-mail: helge.buersing@iosb.fraunhofer.de (H. Bürsing); wolfgang.gross@iosb.fraunhofer.de (W. Gross)

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information, a so-called hypercube. Data acquisition is usually done in one of the following three ways:

1. Push-broom hyperspectral imaging: This approach is most commonly used when a relative movement between sensor and target can be guaranteed, e.g. in bulk material sorting due to objects on a conveyor belt or in remote sensing where the sensor is installed on an airborne platform. It allows recording of one spatial line (swath) while simultaneously collecting all the bands at the same time as outlined in Figure 1. The sensor consists of a two-dimensional (2-D) detector array, an imaging spectrograph, and a lens. This means that only one spatial line can be recorded at a time as the other dimension of the detector is used to record the spectral information. The lens directs reflected light from the target onto the entrance slit of the spectrograph where it is dispersed by a prism or grating. To generate the hypercube, either the target (e.g. bulk sorting), the camera (e.g. remote sensing), or an additional scan mirror (e.g. static measurements) has to be moved perpendicular to the measured line. The advantages of the push-broom HSI are the rugged design and rapid data acquisition.
2. Spectral scanning: The core of this setup is tunable electro-optical filters such as Fabry-Pérot etalon, liquid-crystal tunable filter, and acousto-optical filter. With reduced spectral resolution, it is also possible to mechanically exchange fixed bandpass filters in front of the lens with a filter wheel. Each recorded frame is a mono-colored 2-D image of the scene, and the full hyperspectral data cube is recorded one spectral band after another. These sensors are more difficult for recording moving targets and remote sensing due to the time delay in recording spectral information. A stabilized platform and motion compensation mirrors can be used to keep the scene steady enough to minimize spatial shift, while the filters are modulated [6]. An important feature of spectral scanning sensors is the shorter optical path compared to push-broom sensors. According to Hagen and Kudenov [7], scanning times range from ~1 s for filter wheels, 50–500 µs for Fabry-Pérot and liquid crystal, and 10–50 µs for acousto-optical filters.
3. Snapshot (non-scanning): Collecting 2-D spatial and the complete spectral information simultaneously is also possible. The Fiber Array Spectral Translator, a system of optical fibers with small diameters and distinct ordering in conjunction with a dispersive spectrometer, was already used in 1998 [8]. In recent years, new high-resolution sensors and cameras were developed. By sacrificing part of the spatial resolution and applying different spectral filters in front of the pixels, the full hyperspectral cube can be recorded during one integration time of the detector.With these sensors, handheld real-time hyperspectral mapping is possible with up to 30 cubes/s. These cameras usually operate in the visible and near infrared and can typically record ~2000 spectra per frame with approximately 100 spectral bands each. As the filter is directly on the chip, no separate spectrograph is required, which results in sensor weights of below 1 kg. The low weight and the possibility to georeference the data with only a few ground control points and image-based procedures allow application of HSI on unmanned aerial systems (UAS).

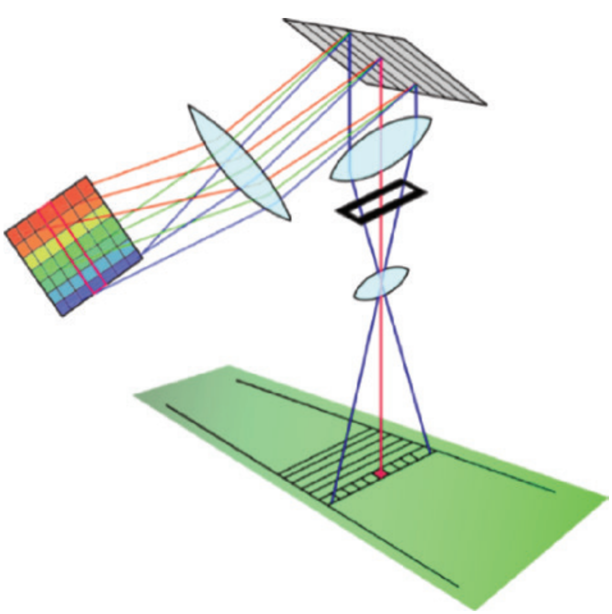

Figure 1: Push-broom HSI schematic. The lens directs reflected light onto spectrometer slit from where it is dispersed via prism/grating onto the detector chip.

Additionally, there are sensors with spatiospectral scanning. These systems consist of a dispersive element in front of a spatially scanning system. The imaging process is similar to the push-broom principle [9]. Up to now, this technique is subject to research and has not been commercially used to the author’s knowledge and will not be discussed further in this article. Table 1 shows a comparison of the aforementioned HSI techniques related to spatial, spectral, and time resolution. In addition, one typical application for each technique is mentioned. The comparison of the different HSI setups is difficult, as each sensor is best used for specific

Table 1: Comparison of HSI techniques with typical sensor performances.

	Signature application	Spatial resolution	Spectral resolution	Time resolution (fps)
Push 1 broom	Remote sensing (VNIR/SWIR), bulk sorting	Function of optics, distance to target and chip size	1 nm VNIR – 5 nm SWIR	~100 lines/s ≙40–100 k spectra/s depending on detector size
Spectral scanning	Remote sensing (MWIR/LWIR), static setup	Function of optics, distance to target and chip size	Adjustable to application in practice	1–100 band images/s, wavelength modulation is bottleneck
Snapshot	Handheld, static setup or close range remote sensing with UAS	Inversely proportional to spectral resolution	~10 nm	~30 cubes/s ≙ approx. 75 k spectra/s

Suitable parameters are subject to the application.

kinds of applications. Spatial resolution for push-broom and spectral scanning sensors can be extremely good. However, recording and tracking of fast-moving objects will lead to artifacts. Snapshot technology, although it generally has a lower spatial resolution, is better suited for moving objects as all the spectra of the image are recorded simultaneously.

Spectral resolution is usually tailored to the application. Most manufacturers build their sensors with spectral resolutions around 1 nm in VNIR and 5 nm in SWIR, which is deemed enough to resolve distinct spectral features that allow robust detection or classification of a specific material. Snapshot cameras usually have a slightly lower spectral resolution due to the filter on-chip manufacturing process. Furthermore, they are not yet available for the SWIR.

Time resolution depends, on the one hand, on the exposure time per frame, on the other hand, on how fast the detector chip can capture the data. As the chips are usually the same material for each sensor type per wavelength range, this parameter can be treated as a constant. For spectral scanners, time resolution is lower due to the fact that modulation time of the filter needs to be added to the equation. However, it is possible to restrict the data acquisition to the important bands for a given task and, thus, improve time resolution.

3 Applications

With the highly resolved spectral information, it is possible to detect narrow features in the spectral signatures or exploit the whole shape of the signature. This opens up completely new possibilities to address certain tasks. The difficulties now lie in developing suitable models that allow robust analysis. Researchers all over the world strive to find better solutions exploiting HS data or apply them to new tasks.

The following list records an introduction to applications, which are related to security systems.

1. Disaster management, early warning system and aftermath coordination: HSI can help in multiple ways for disaster management. Earthquakes and tsunamis can damage infrastructures of factories and pipelines. Detecting, monitoring, and mapping of oil spills or leaking chemicals or gas can help minimize environmental damages and contamination, which in turn prevents an expensive and dangerous cleaning process. Most of the potentially dangerous materials have spectral signatures that possess distinct spectral features. In most cases, they differ from the natural environment, which makes them easy to detect with HSI with minimal false alarms. An example for oil spill detection can be found in Ref. [10]. Gas leaks can easily be detected with HSI operating in the mid- or long-wave infrared. Examples and in-depth discussion of the underlying physics can be found in Refs. [11] and [12]. Another possible application for HSI is to support maintenance of dikes for flood prevention. Usually, vegetation is grown on dikes to make them more durable as the roots strengthen the dike's body and prevent erosion. However, when the vegetation dies due to draughts or pest infestation, the dike becomes less durable. Regular inspection of vegetation with HSI can help with early detection as healthy vegetation can easily be differentiated from stressed or infected vegetation. This can help perform early countermeasures.

However, to actually use HSI for these applications, several aspects need to be considered. Hyperspectral data and the derived classification maps need to be available as fast as possible. If data preprocessing takes too long, environmental hazards might spread in the meantime, and mapping might no longer be accurate. The Fraunhofer IOSB has designed a system consisting of HSI, high-resolution RGB, and broadband LWIR cameras integrated into a wing pod that can be attached to a potentially remote-controlled motor glider. A framework has been set up to stream the data in real time to a ground control station, to automatically perform basic preprocessing and georeferencing and to support the distribution of data over the internet to analysts all over the world [13]. [The model workflow is depicted in Figure 2.] The system will be augmented in the future with a LiDAR system to simultaneously generate detailed ground elevation models. Other applications for this system are monitoring illegal deforestation and tracking pest infestation of forests. Airborne hyperspectral data were already used during the Deepwater Horizon oil spill in 2010, related research to improve future crisis management can be found in Ref. [14].

2. Warning system for dangerous substances: A prime example is the detection of explosives. HSI is used in conjunction with laser-induced breakdown spectroscopy and Raman spectroscopy to actively illuminate a sample and detect possible traces of different explosives like TNT [15]. The goal is a standoff detection method that could be used in airports, embassies, or other facilities that require heightened security. Depending on the sensitivity, this approach could be used together with chemical swipes, so-called sniffers, as a two-step confirmation. HSI can be used to monitor people walking by; the sniffers are used as confirmation, when something is detected. Robustness of this approach is still under research as traces of explosives on clothing can be very low. The spectral signature of the explosive material needs to be separated from its background. A controlled environment with ideal illumination conditions will likely be mandatory.

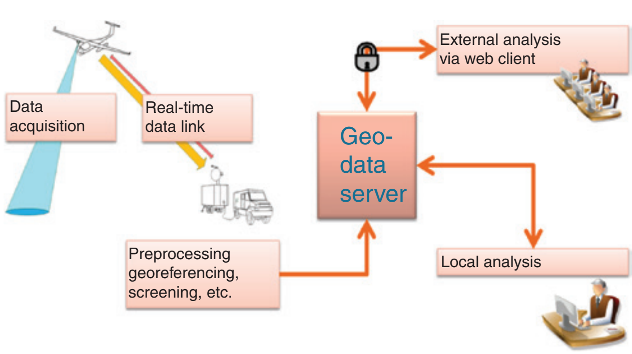

Figure 2: System concept for disaster management using HSI, high-resolution RGB, and long-wave infrared sensors with the goal to send data to a ground control station including automatic preprocessing. Data can be analyzed on-site or accessed via web client.

3. Incoming control: Fraud and counterfeit detection: The task of identifying people is quite common, and standard RGB or black and white cameras together with advanced algorithms have a good recognition statistic. The idea is to use HSI for cases where other approaches fail. HSI is already used for detection of forged documents like passports, birth certificates, etc. [16]. It can also be used to detect counterfeit clothing. In the context of civil security, HSI can be used to detect a possible impostor that tries to get entry to high-security areas by using professional makeup, fake uniform, and forged documents. When makeup is used to disguise the facial features and prevent recognition with cameras, HSI also is not able to identify the person underneath. However, it can clearly detect the presence of makeup, which can be enough to warrant closer inspection. Since an optimized system requires fast and robust detection to efficiently handle the people waiting in line, this approach profits the most in cooperative environments with predefined illumination.
4. Harbor monitoring: ship identification: Harbor monitoring has a lot of security reasons. Identifying incoming ships and synchronizing their permissions can help to detect potential smugglers or other threats. The task is to distinguish between regular and suspicious activities. As the area is large, and activity analyses are complicated, different approaches are investigated [17]. At this point, it is not clear which technique will be the best. For this application, an approach where individual ships can be tracked and recorded with HSI is necessary. This application would be difficult for push-broom or spectral scanning HSI due to the fast-moving objects. Snapshot cameras could be used, but further testing is required to check how well snapshot sensors can be combined with zoom lenses to achieve the required stand-off capability and spatial resolution.

So far, other sensor systems, like synthetic aperture radar, broadband cameras, chemical swipes, etc., are predominantly used for these applications, but current research demonstrates the value of using HSI, either to supplement or as a stand-alone method. A main drawback is the complicated pre-processing required. Especially in areas where illumination and atmosphere cannot be controlled, automatic procedures can lead to errors and impede data exploitation.

The described applications have something in common: It is theoretically possible to solve the tasks using only a subset of spectral bands that is tailored to the application. This, however, requires a deterministic description of possible materials that need to be differentiated. This strongly relies on a closed system or at least a cooperative environment. While some tasks are relatively simple, e.g. differentiating between clear skin and makeup, some are more difficult as they change with time, e.g. counterfeit materials might adapt to the detection method, or unforeseen materials can occur and hinder analysis. In these cases, it pays off to have a full hyperspectral sensor available as then, only the algorithm, but not the sensor, needs to be updated. Most notable are scenarios with an uncooperative environment and target. Surveillance of crowds to prevent terrorist attacks is extremely difficult. One possible approach is to use a spectral database of potentially dangerous materials and use matched filters or other classification algorithms to detect them [18]. Another way of analyzing the data is to look for anomalies, in general, and give out an alarm, which needs to be analyzed separately for confirmation. In highly complex scenarios, the number of false alarms can be problematic.

4 Challenges and outlook

To summarize the status and outlook of the potential of hyperspectral imaging, there are three challenges:

1. Understanding the task: HSIs allow to measure images with spectral resolution, but to solve the task of discrimination between, e.g. different materials one needs to find the significant feature in the spatial-spectral data cube. Once the differences between 'background' (things of no interest) and the 'object of interest' are determined, everything else can be optimized. Finding task-specific significant features is still challenging for many applications. Here, HSI in the correct wavelength range have to be chosen. Lately, the use of HSI in the mid- and longwave infrared has become more feasible. They are predestined to detect traces of gas, but are also more difficult to use on a moving platform due to employing the spectral scanning approach. Also, risk assessment is a necessary step in dealing with false alarms. When single-pixel detection is not vital, spatial methods to reduce the false-alarm rate can be used, while repeating data acquisition can increase robustness when the task is not time sensitive.
2. Finding a setup, which allows to get the information necessary for solving the task: The difficulty of working with hyperspectral data lies in the amount of information recorded. Some bands contain redundant information; others mainly record atmospheric noise. Finding a suitable subset of bands that solve a given problem can be difficult. This is important for designing a multispectral camera tailored to a specific application, e.g. if distinct spectral features exist, and complete hyperspectral data would only supply redundant information. Additionally, data preprocessing is extremely important to eliminate unwanted effects like changes in illumination or viewing angle.

   It can be very helpful to influence the environmental conditions for data acquisition if possible. This means to actively illuminate with a suitable source to increase the signal-to-noise ratio of the data, but also selecting proper values for sensor parameters, e.g. frame rate, exposure, spectral or spatial binning, etc. Another aspect is the selection of sensor technology as explained in chapter 2.
3. Handling of the data: big data: A vital part of monitoring for potential threats is the quick availability of data and data products. For disaster management and surveillance, real-time data acquisition, preprocessing, and analysis may be required. While the amount of data can usually be handled, it is beneficial to have a setup that also sends the data to a ground control station, performs automatic preprocessing, and allows remote access to data analysts all over the world [13].

To summarize, HSI can be used for a manifold of applications in the field of civil security and beyond. Researchers all over the world are working to develop new algorithms to improve data exploitation. A main goal is to improve performance and to automatize evaluation with the goal to use HSI in real-time scenarios. Further information can be found in Refs. [19–21].

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Helge Bürsing
Fraunhofer-Institut für Optronik Systemtechnik und Bildauswertung, Standort Ettlingen, Scene Analysis, Ettlingen Germany
helge.buersing@iosb.fraunhofer.de

Helge Bürsing was born in Gifhorn, Germany in 1972. He obtained the German Abitur in 1994. In 2002, he finished his PhD thesis at the Max-Planck-Institute for biophysical Chemistry in Göttingen and began working at the Fraunhofer Institute for Optronics, System Technologies and Image Exploitation. After managing and working in different projects in the field of optronics such as DIRCM, fs-laser beam propagation, sensor hardening and HEL, he became head of the Optronics department in 2013.

Wolfgang Gross
Fraunhofer-Institut für Optronik Systemtechnik und Bildauswertung, Standort Ettlingen, Scene Analysis, Ettlingen Germany
wolfgang.gross@iosb.fraunhofer.de

Wolfgang Gross was born in Karlsruhe, Germany, in 1985. He obtained the German Abitur in 2004. After being awarded a Diploma in Techno-Mathematics from the University of Karlsruhe (KIT) in 2011, he began working toward a PhD in cooperation with the Fraunhofer Institute for Optronics, System Technologies and Image Exploitation. His research focuses on hyperspectral image exploitation, spectral unmixing, and nonlinear representation of large point clouds.