

Review of Hyperspectral Imaging in Environmental Monitoring Progress and Applications

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Abstract: New, smaller and easy-to-carry hyperspectral imaging systems are changing the way we monitor the environment. These systems use advanced sensors to get information from the environment and can be used from the sky, like using a drone, or from the ground. This article talks about how we've been able to make these sensors smaller and more portable, and how we've started using cheap, everyday technology for these tasks. Right now, these systems help the existing ways we monitor the environment, but as this technology keeps getting better, we're expecting these new tools will be able to do the job all on their own soon. Even though these devices are cheap and light, they're already giving us high-quality scientific data. This means more people can use this technology, and we'll be able to collect a lot more information about our environment. So, this paper will provide a brief review of developments and technological advances in compact field deployable systems by using hyperspectral imaging sensors.

Keywords: Hyperspectral, Field monitoring, Miniaturization, Imaging system, Field deployable.

1. Introduction

For the past 30 years, hyperspectral imaging, which creates detailed pictures by capturing light from many parts of the spectrum, has been useful for many tasks[1-5], like studying the Earth's surface[5], preserving art, and exploring ancient sites[6]. This technique was first developed in the late 1960s[7], but recent improvements in technology have made it possible to get even more detailed images. Hyperspectral images are unique because they have two spatial dimensions (like length and width) and one spectral dimension (which measures different types of light). The spatial dimensions show the relationship between the pixels in an image, while the spectral dimension shows changes in light within the pixels. This data can be shown as a 3D cube, where each "slice" represents a specific type of light.

This technology was first used to study the Earth from afar, but now it can capture images across hundreds of tiny bands within the visible, near-infrared, and mid-infrared parts of the spectrum[8]. This allows us to create a nearly continuous spectrum for each pixel in a scene, giving us a detailed look at features we might not see with simpler scanners. Because of these advancements, hyperspectral imaging is now used in many fields to monitor our environment in new ways[2, 4, 9]. In recent years, there has been a lot of interest in using portable hyperspectral imaging for environmental monitoring. This is a promising development that could change how we gather and understand data. This article reviews the current state of this technology, with a focus on how it's become smaller, more portable, and cheaper, and how it's being used in a variety of environmental fields.

To gather information for this article, we searched for articles using terms like "low-cost," "miniaturization," "hyperspectral," and "environmental monitoring." We searched online databases to find key researchers and leading research in this field[10, 11]. We also studied different ways of using hyperspectral imaging to get a thorough

understanding of the topic. However, we didn't include information about satellite-based applications in this article because they aren't directly related to the focus on portable devices. In this review, we've collected detailed information about different design approaches, who's leading the research, the nature of the research, and how it fits into the bigger picture. Besides, this development can benefit other research areas including social science[11, 12], plasma physics[13, 14] and medical research[15].

2. Sensor

Hyperspectral imaging, or the process of taking detailed pictures using light from many parts of the spectrum, generated from electron excitation[16, 17], can be done in many ways and with different types of sensors. These sensors are often categorized by how they're arranged, how many different types of light (or spectral bands) they can capture, and how they take pictures. One type of sensor, called a push broom sensor, has been commonly used for taking large images from the air. Recently, these sensors have been made smaller and are now used in drones. This type of sensor is liked because it captures a lot of detail in both space and light. However, it takes pictures by recording a line of light information at a time, which can make the images difficult to process afterward. Another type of sensor, called a whiskbroom sensor, takes images of one spot at a time. It uses a rotating mirror to scan a line that's at right angles to the direction the sensor is moving. These sensors have similar problems to push broom sensors, but they also take images more slowly, which means gathering all the data takes longer. Also, the rotation of the mirror can distort the image. Despite these challenges[18, 19], recent research has shown that it's possible to create affordable whiskbroom sensors that can be used in drones. This spectrum-based sensor devices and its usage can be optimized by data-driven approaches[20], which is currently under the study.

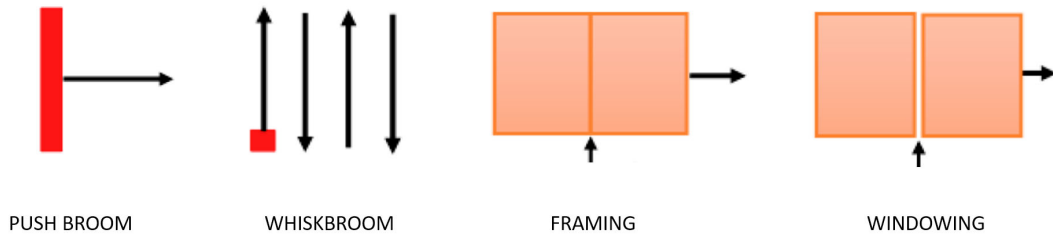


Figure 1. Various sensor types employ distinct approaches to capture images. Push broom and whiskbroom scanners, for instance, capture images pixel by pixel, whereas framing and windowing instruments can capture a complete 2-Dimensional image simultaneously. This variation in capture methods can result in challenges for pixel-based instruments, such as image distortion caused by optic rotation, as mentioned previously.

3. Technological Developments and Challenges

Right now, hyperspectral imaging, or the process of taking detailed pictures using light from many parts of the spectrum, is mostly done by satellites or planes. Recent advances in these airborne and spaceborne technologies are giving users a lot of detailed spectral, spatial, and time-based information[21]. As a result, this technology is now well-used in the remote sensing field, with a broad range of applications. The development of tiny CubeSat satellites, like HyperCube, shows promise for the future development of lightweight, low-cost image capture from space[22]. But while these sensors can analyze large areas of the Earth's surface and provide large datasets over long periods of time, they have limitations. They're often limited by factors like cloud coverage and the amount of detail (or spatial resolution) they can capture. Furthermore, manned aerial surveys can be expensive and depend heavily on good weather. These limitations can make these types of measurements unsuitable for many smaller, local applications.

Jaud and colleagues pointed out a big gap between the detailed outputs of local field surveys and the less detailed outputs from satellite and aerial sensors[23]. However, with the development of drone platforms over the last decade, we now have an intermediate option: drones equipped with hyperspectral sensors. These drone-based platforms offer more flexibility than traditional methods, allowing users to adjust factors like survey size and flight altitude to suit their needs. Plus, because drones are typically small and lightweight, they're easy to store and deploy.

Several drone-equipped hyperspectral sensors have been tested recently in a variety of fields. For example, Habib and colleagues used a low-cost drone-based hyperspectral scanner in precision agriculture. Their drone provided detailed imagery of the survey area, but they ran into difficulties when trying to geo-rectify, or correctly place, the images on the Earth's surface. Jaud and colleagues [23] ran into similar complications with their push broom drone sensor, finding that the process of forming images line by line added complexity to the geometric correction step.

4. Application

There's a lot of potential and progress being made in the development of compact, portable hyperspectral imaging sensors for various environmental monitoring applications. Especially exciting is the potential for integrating affordable, high-quality consumer market components. This could really help to bring hyperspectral imaging into more common use within environmental monitoring. As a result, a wide variety

of devices have been developed for sensing applications across different conditions. Because these conditions can vary significantly, the devices needed can also be quite different in terms of factors like size, weight, and sturdiness. This section will discuss developments across these different environments, focusing on some key examples to illustrate the current state-of-the-art in the field. Throughout this section, when we say "low-cost", we're referring to hyperspectral devices that are often built in-house using mass-produced components. This allows for the overall build costs to be much lower than those of commercial, scientific-grade instruments.

On the other hand, Chennu et al. [80] talk about creating a device operated by divers for monitoring shallow underwater areas like coral reefs. This is the first device of its kind, and it offers a big, cost-effective boost in collecting hyperspectral data for these environments. It gets around the difficulties caused by the path of light through the atmosphere and water, which is a problem with observations made from above the water surface. While the picture quality of this sensor was not as high as some digital camera imagers, it was still able to identify the unique light reflection features of corals at the level of individual organisms. This device is user-friendly and doesn't require any special skills to operate, but it's currently too big to use with unmanned platforms. This shows a big opportunity for future research.

5. Conclusion

In summary, this article offers a quick overview of the latest small-sized, affordable, and portable hyperspectral technologies being used in environmental monitoring. It's clear that this is a fast-growing area of research with the potential to radically change environmental monitoring across many fields. This makes it a perfect time to record the current best practices. Right now, these devices mainly serve as additional tools to existing monitoring techniques. However, as technology keeps improving, we expect these devices to be used more and more for independent monitoring. Future efforts should focus on expanding the uses for these devices, especially making them work well in extreme environments, and making the most of the reduced cost of technology available to consumers. With the most recent affordable devices now producing high-quality scientific results, it seems like hyperspectral imaging with smartphones is set to become an exciting new direction in practical environmental science. This could greatly increase the accessibility of hyperspectral image capture. We believe this article captures the start of a rapid increase in community adoption, expanding the technology's use far beyond the application areas currently explored.

References

- [1] M.J. Khan, H.S. Khan, A. Yousaf, K. Khurshid, A. Abbas, Modern trends in hyperspectral image analysis: A review, *Ieee Access* 6 (2018) 14118-14129.
- [2] Y. Tang, S. Song, S. Gui, W. Chao, C. Cheng, R. Qin, Active and Low-Cost Hyperspectral Imaging for the Spectral Analysis of a Low-Light Environment, *Sensors* 23(3) (2023) 1437.
- [3] D. Huang, Y. Tang, R. Qin, An evaluation of PlanetScope images for 3D reconstruction and change detection—experimental validations with case studies, *GIScience & Remote Sensing* 59(1) (2022) 744-761.
- [4] S. Gui, R. Qin, Y. Tang, Sat2lod2: A Software For Automated Lod-2 Modeling From Satellite-Derived Orthophoto And Digital Surface Model, *arXiv preprint arXiv:2204.04139* (2022).
- [5] P. Ghamisi, N. Yokoya, J. Li, W. Liao, S. Liu, J. Plaza, B. Rasti, A. Plaza, Advances in hyperspectral image and signal processing: A comprehensive overview of the state of the art, *IEEE Geoscience and Remote Sensing Magazine* 5(4) (2017) 37-78.
- [6] H. Liang, Advances in multispectral and hyperspectral imaging for archaeology and art conservation, *Applied Physics A* 106 (2012) 309-323.
- [7] M.C. Govender, K. Bulcock, H.(2007)“A review of hyperspectral remote sensing and its application in vegetation and water resource studies”, *Journal of Water South Africa* 33(2).
- [8] T. Adão, J. Hruška, L. Pádua, J. Bessa, E. Peres, R. Morais, J.J. Sousa, Hyperspectral imaging: A review on UAV-based sensors, data processing and applications for agriculture and forestry, *Remote sensing* 9(11) (2017) 1110.
- [9] M. Kirsch, S. Lorenz, R. Zimmermann, L. Tusa, R. Möckel, P. Hödl, R. Booyesen, M. Khodadadzadeh, R. Gloaguen, Integration of terrestrial and drone-borne hyperspectral and photogrammetric sensing methods for exploration mapping and mining monitoring, *Remote Sensing* 10(9) (2018) 1366.
- [10] Zeng Qingfeng, Gao Ruiquan, Wen Jingmin, Li Lei, Xu Lei, Tang Yang, Lai Xin, An IoT-based microclimate environment observation and management model for urban cells, *Collection* 3 (2019).
- [11] T. Yang, Y. Kawahara, T. Asami, D. Bollegala, BS-1-12 Analyzing Patterns from Twitter Happiness referring Stock Market and American Unemployment Rate Announcement, *Proceedings of the General Conference of the Electronic Intelligence and Communications Society* 2013(2) (2013).
- [12] T. Yang, Y. Kawahara, T. Asami, D. Bollegala, Analyzing Patterns from Twitter Happiness referring Stock Market and American Unemployment Rate Announcement, (2013).
- [13] J. Huo, S. Selezneva, L. Jacobs, Y. Cao, Study of wall ablation on low-voltage arc interruption: The effect of Stefan flow, *Journal of Applied Physics* 125(21) (2019) 213302.
- [14] J. Huo, Y. Cao, Interfacial potential barrier induced constriction and stepwise transition of a dynamic arc root, 2019 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), IEEE, 2019, pp. 564-567.
- [15] G. Lu, B. Fei, Medical hyperspectral imaging: a review, *Journal of biomedical optics* 19(1) (2014) 010901-010901.
- [16] J. Huo, J. Ronzello, A. Rontey, Y. Wang, L. Jacobs, T. Sommerer, Y. Cao, Development of an arc root model for studying the electrode vaporization and its influence on arc dynamics, *AIP Advances* 10(8) (2020) 085324.
- [17] N. Wang, K. Davis, M. Sotzing, M.A. Baferani, J. Huo, C.B. Carter, R. Gerhard, Y. Cao, Flexible nanogenerator with 3D-printed ferroelectrets, 2021 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), IEEE, 2021, pp. 375-378.
- [18] Y. Tang, J. Yan, Y. Wu, J. Hong, L. Xu, Z. Lin, Design of Remote Sensing Image Data Analysis and Processing Platform Based on Environmental Monitoring, *Journal of Physics: Conference Series*, IOP Publishing, 2021, p. 012056.
- [19] X. Lai, Y. Tang, L. Li, P. Chan, Q. Zeng, Study on microclimate observation network for urban unit: A case study in a campus of Shenzhen, China, *Physics and Chemistry of the Earth, Parts A/B/C* 110 (2019) 117-124.
- [20] J. Huo, Y. Wang, N. Wang, W. Gao, J. Zhou, Y. Cao, Data-driven design and optimization of ultra-tunable acoustic metamaterials, *Smart Materials and Structures* 32(5) (2023) 05LT01.
- [21] R.G. Sellar, G.D. Boreman, Classification of imaging spectrometers for remote sensing applications, *Optical Engineering* 44(1) (2005) 013602-013602-3.
- [22] R. Glumb, M. Lapsley, D. Lee, P. Mantica, J.-P. Dery, TRL6 testing of a hyperspectral infrared CubeSat instrument, *AIAA SPACE and Astronautics Forum and Exposition*, 2017, p. 5322.
- [23] M. Jaud, N. Le Dantec, J. Ammann, P. Grandjean, D. Constantin, Y. Akhtman, K. Barbieux, P. Allemand, C. Delacourt, B. Merminod, Direct georeferencing of a pushbroom, lightweight hyperspectral system for mini-UAV applications, *Remote Sensing* 10(2) (2018) 204.