Snapshot hyperspectral imaging and practical applications

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ABSTRACT
Traditional broadband imaging involves the digital representation of a remote scene within a reduced colour space. Hyperspectral imaging exploits the full spectral dimension, which better reflects the continuous nature of actual spectra. Conventional techniques are all time-delayed whereby spatial or spectral scanning is required for hypercube generation. An innovative and patented technique developed at Heriot-Watt University offers significant potential as a snapshot sensor, to enable benefits for the wider public beyond aerospace imaging. This student-authored paper seeks to promote awareness of this field within the photonic community and its potential advantages for real-time practical applications.

Keywords: Hyperspectral, imaging, real-time, sensor, applications, search, rescue, ophthalmology, foodstuffs, landmines

1. CONVENTIONAL AND HYPERSPECTRAL IMAGING

Conventional imaging techniques involve the digital representation of a remote scene by employing a reduced colour space. This involves considering only certain wavebands in the complete spectrum, in order to reduce processing time and storage needs. The use of these colour spaces is partly motivated by the biology of the human eye, which responds most efficiently in three wavebands. Reduced representation henceforth allows RGB recorded scenes to be perceived by the human eye as complete and continuous, even though large amounts of spectral information are not recorded.

The availability of limited spectral information can make certain image elements appear alike to the human eye, where otherwise identical colours do not reflect the underlying spectral diversity. Hyperspectral imaging (HSI) on the other hand, has an additional spectral dimension of up to several hundred wavebands, which better reflects the continuous nature of actual spectra. The traditional 3D RGB or 4D CMYK colour spaces can then be merely considered as part of an N-dimensional hyperspace, where N is the number of wavebands. The main benefit of HSI with respect to conventional imaging is that image elements that previously appeared as mutually indistinguishable can now be potentially differentiated or even positively identified.

Conventional pixels consequently map to hypercubes with N components or "colours", as opposed to only three or four components for RGB and CMYK respectively. Figure 1 is an illustration of mapping conventional pixels to hyperpixels when using a HSI detector. The foreground 2D image represents a conventional image composed of many RGB pixels, whereas the perspective depth shows the spectral dimension of a corresponding hypercube. This is only a graphical overview and is not indicative of a true hypercube, which is in reality an abstract mathematical construct.
Figure 1: An example of a hyperspectral image rendered onto 2D flat media – image from AVRIS platform released by NASA

Spectral reflectance is the parameter of interest within HSI, where the reflected to incident ratio of light is a function of the particular wavelength involved. Each type of natural or synthetic terrain feature has a unique spectral signature, with a characteristic form and notable absorption bands thus allowing discrimination and identification. Figure 2 demonstrates examples of these unique spectral signatures for various surfaces. These HSI “fingerprints” are otherwise unique to the surface in question, allowing a human operator using detection algorithms to locate regions of interest.

Figure 2: Reflectance spectra of green vegetation compared to a spectral curve for dry and yellowed grass (from MicroImages Inc)

2. TIME-DELAYED HYPERSPECTRAL TECHNIQUES

Spaced-based and high-altitude HSI is currently employed by the geophysical community for environmental monitoring of pollution, agricultural surveys of land usage, in addition to scouting for natural minerals and resources. This is achieved through a time-delayed application of HSI, where hyperspectral images are recorded and returned-to-base for extensive processing at a later point in time. User-friendly HSI commercial packages such as ENVI are prevalent within the private sector for time-delayed applications.

Imaging spectrometers are employed in time-delayed HSI, in a form of remote sensing spectroscopy that generally uses dispersive elements. The first imaging spectrometers involved raster scanning the surface of the Earth in a sequential manner, followed by subsequent image assembly of the scanned areas. This can be compared to the method by which the older CRT televisions and monitors build-up images from scanning lines. Given the relatively few wavebands employed at the time (less than ten), this type of imaging can now only be considered as multispectral with respect to modern developments. Contemporary HSI systems like the Hyperion EO-1 sensor can involve over two hundred narrow wavebands, compared with the early satellite imagers, such as SPOT XS and the LandSat Thematic Mapper.
3. NOVEL REAL-TIME HYPERSPECTRAL IMAGING

Conventional HSI techniques are fundamentally time-delayed whereby temporal, spatial or spectral scanning is required in order to function properly. The traditional use of dispersive elements, such as prisms or gratings, requires using time intervals to build-up a complete hyperspectral image of the scene under consideration. This basic requirement renders real-time anomaly detection in critical situations either unfeasible or greatly prohibitive if possible at all. In order to widen the application of HSI away from platforms such as satellites or high-altitude planes, real-time imaging is required that can take instant snapshots without scanning.

An innovative and patented technique developed at Heriot-Watt University offers significant potential for a snapshot HSI sensor, to enable benefits for the wider public beyond aerospace imaging. The premise of the IRIS sensor involves employing Wollaston prisms as polarising beam splitters as shown in Figure 3 below. For reference of readers, IRIS is a convenient acronym for Image-Replicating-Imaging-Spectrometer. Each waveplate and prism combines into one pair that splits each input image into two more, with each otherwise identical image having a different wavelength. The three pairs within the following figure each successively double one input image into eight separate spectral images.

![Image of IRIS sensor and a spectral image of a human retina](image)

Figure 3: Schematic of IRIS and a spectral image of a human retina, with images courtesy of Heriot-Watt University

Exploiting this wavelength and polarisation dependence of each waveplate-prism pair allows the IRIS system to replicate an image into separate wavebands. Unlike time-sequential filtering with conventional methods, the theoretical throughput of the initially polarised light is unity. There is no rejection of light and only minor losses occur through reflections, which can be minimised by coatings and bonding. The net effect is to provide an improved signal-to-noise ratio that can be up to an order of magnitude higher with respect to established spectral imagers. The opportunity exists for two IRIS systems operating in tandem to record both spectral and polarimetric data. This would offer theoretical throughput of all light along with the opportunity for polarimetric and spectral imaging at exactly the same time.

The IRIS sensor is presently in development for ophthalmic diagnosis, where functional mapping of blood flow within the human retina is carried out. Snapshot-HSI using IRIS can provide information on oxygen saturation, to locate retinal areas that are lacking in nutrient supply. This can be indicative in diabetes or localized occlusions, which are leading factors in permanent blindness and visual defects. Clinical trials within NHS hospitals are presently in progress and it is hoped snapshot HSI enabled by IRIS can provide tangible benefits for patients suffering from certain conditions.

4. PRACTICAL APPLICATIONS WITHIN REAL-TIME

Real-time HSI can also provide an enhancement to low-light Search and Rescue (SAR) operations, by negating the debilitating effects of thermal crossover in infrared imagery. This phenomenon normally occurs on a diurnal cycle when conditions are such that there is a contrast loss between adjacent objects. It causes the target of interest to exhibit the same temperature as its immediate surroundings, thus becoming indiscernible within infrared imagery.

Thermal crossover is an interaction between weather effects and solar heating, which normally becomes apparent during the early morning and late afternoon. Dense clouds can reduce the thermal contrast caused by solar
heating, while strong winds move the surface temperature of objects towards that of the ambient. During calm conditions of intense sunlight without cloud cover, thermal crossover may only ideally persist for a few seconds at most. Unfavourable conditions of dense cloud, strong winds and heavy precipitation can extend this effect for several minutes.

Thermal crossover can effectively render a SAR operation as sightless, especially in extremely low-light conditions when visual image intensifiers are not effective. During highly time-critical SAR operations, whether on the open seas or difficult terrain, thermal crossover can cause rescue aircraft to miss the search target. This can result in dangers involving loss of human life, especially if incapacitation and physical injury are involved. An HSI sensor operating in multiple bands could significantly reduce thermal crossover in IR imagery. This would result from the fact only a single waveband would suffer from thermal crossover at any one particular time. Exploiting HSI to negate this debilitating effect for SAR operations would considerably enhance the ability of rescuers to save human life.

Unmarked minefields pose an ethical and moral challenge, whereby they constitute a persisting threat that cannot distinguish between the enemy and non-combatants. Numerous civilian causalities continue to be incurred by landmines after the cessation of hostilities and facilitating redevelopment requires removal. Demining in a civilian context is far more restrictive than military means, where the only method meeting the UN ethical criteria for International Mine Action Standards is manual disarmament. Demining is a usual prerequisite for humanitarian operations and it is estimated that manually clearing a single square kilometer of land can consume up to two million USD. This is due to inefficient metal detection statistically yielding one thousand false positives for every mine, even assuming that low-metals mines are not present.9

Deploying an HSI detector for anomaly detection onto a low-altitude, small UAV for civilian applications could greatly reduce the cost of demining.10 Manual minesweepers would be able to clearly locate unmarked minefields from unaffected areas and hence concentrate their efforts on areas of the greatest threat to the civil population. When manual minesweepers are unable to attend a given area, then at least the minefield can be clearly defined and marked, thus immediately preventing more loss of human life.

Another example of HSI benefit is the identification of damaged produce and meat on sorting belts, whereby such damage or bruising exhibits certain subtle infrared features.11 This can help reduce waste whereby consumers reject damaged goods, which may only become apparent after they have left the sorting factory. Exploiting HSI on the production line could identify these goods and reroute them into other uses such as soups or juices, thus preventing waste at the grocery store through consumer rejection.12 Exploiting a snapshot sensor such as IRIS could reduce many tonnes of food wastage in developed and emerging economies, especially if leveraged en-masse throughout the foodstuffs industry.

5. CONCLUSIONS AND OUTLOOK

Enabling snapshot HSI for real-time applications could provide numerous benefits that could extend beyond the topical examples given previously. Whether within the ophthalmic lab, maritime oceans or the food production line, moving beyond imaging with merely a few colours could open many opportunities. The IRIS sensor as described could be considered as an enabling technology, to transfer the benefits of HSI from the aerospace domain and into wider society. Increasing awareness of IRIS for snapshot HSI is crucial to finding new applications within varied fields, some of which could appear as initially unexpected. The student author of this paper is currently involved with the IRIS sensor, while also hoping to contribute to stimulating a discussion of real-time HSI and its benefits to the wider scientific community.

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REFERENCES

[1] Randall B Smith, Introduction to Hyperspectral Imaging, MicroImages Incorporated, Lincoln NE (July 2006)
[2] Rick Blum and Zheng Liu, Multi-Sensor Image Fusion and Applications, CRC Francis & Taylor, pg 330 (July 2005)
[3] Andrew Harvey and David Fletcher-Holmes, “Imaging Apparatus” International Patent WO2004-005870-A1 (2004)
[4] AR Harvey et al, “Imaging Spectrometry at Visible and Infrared Wavelengths using Image Replication” Proceedings of SPIE, Volume 5612, pages 190-198 (2004)
[5] Andrew Harvey et al, “Spectral Imaging in a Snapshot” Proceedings of SPIE, Volume 5694, pages 110-119 (2005)
[6] Ied Alabboud et al, “New Spectral Imaging Techniques for Blood Oximetry in the Retina” Proceedings of SPIE, Volume 6631, Paper 66310L (July 2007)
[7] Andrew Harvey et al, “Hyperspectral Imaging for the Detection of Retinal Disease” Proceedings of SPIE, Volume 4816, pages 325-335 (July 2002)
[8] USAF and US Army, Weather Support for Army Tactical Operations, FM 34-81/AFM 105-4 (31st August 1989)
[9] UN Mine Action Service, Mine Action Standards, UN Peacekeeping Operations Dept, New York (19th March 2007)
[10] Jacqueline MacDonald et al, Alternatives for Landmine Detection, RAND Corp, Santa Monica CA (25th May 2003)
[11] Jun Qiao et al, “Determination of Pork Quality Attributes Using Hyperspectral Imaging Techniques” Proceedings of SPIE, Volume 5996, paper 59960M (November 2005)
[12] Diwan Ariana et al, “Detection of Mechanical Injury on Pickling Cucumbers using Infrared Hyperspectral Imaging” Proceedings of SPIE, Volume 5996, paper 59960P (November 2005)