Sensor Fusion and Learning Workshop

Hyperspectral and Multispectral Imaging

Centre for Automation and Robotics CSIC-UPM

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Introduction

- Spectral imaging combines the strength of conventional imaging with that of spectroscopy to accomplish tasks that each cannot perform separately.

- The product of a spectral imaging system is a stack of images of the same object or scene, each at a different spectral narrow band.

- The field of spectral imaging is divided into three techniques:
  - Ultraspectral
  - Hyperspectral
  - Multispectral
**Introduction**

- **Ultraspectral** is typically reserved for interferometer-type imaging sensors with a very fine spectral resolution and deals with more than 200 bands.
- These systems often have a low spatial resolution of several pixels only, a restriction imposed by the high data rate.
- **Hyperspectral** deals with imaging at narrow spectral bands (usually about 100-250 spectral bands) over a contiguous wavelength range, and produces the “spectra” of all pixels in the scene.
- **Multispectral** deals with several images at discrete and fairly narrow bands – usually fewer than 30.
Hyperspectral Imaging System

- All systems have the same basic components in common:
  - a means to image the object
  - a means to provide both spectral and spatial resolution
  - a means to detect.

- The complete optical system for a hyperspectral imaging device consists of:
  - a suitable objective lens matched to the spatial and spectral requirements of the application
  - a wavelength dispersion device such as an imaging spectrograph
  - a two-dimensional detector such as a CCD or a CMOS camera to simultaneously collect the spectral and spatial information.
Hyperspectral Data and Hyperspectral Image

- Hyperspectral data consists of several images representing intensities at different wavelength bands composed of voxels containing two-dimensional spatial information (of m rows and n columns) as well as spectral information (of K wavelengths).
- These data are known as a three-dimensional hyperspectral cube, or hypercube, data cube, data volume, spectral cube or spectral volume.
- Therefore, a hyperspectral image described as \( I(x, y, \lambda) \) can be viewed either as a separate spatial image \( I(x, y) \) at each wavelength \( (\lambda) \), or as a spectrum \( I(\lambda) \) at every pixel \( (x, y) \).
Acquisition modes of Hyperspectral images

There are three conventional ways to build one spectral image:

- **Point scanning – Whiskbroom**:
  - scans a single pixel at a time.
  - The image is recorded with a double scanning step: one in the wavelength domain and the other in the spatial domain.

- **Area scanning – Wavelength scanning**
  - It is used to acquire a sequence of 2D images at different wavelengths.
  - Disadvantage: the requirement for repetitive scanning of the same target at several wavelengths.

- **Line scanning – Pushbroom**
  - It is used to acquire a sequence of line images in which a complete spectrum is captured for each pixel on the line.
Calibration Techniques

- Calibrating the hyperspectral imaging system is vital before acquiring the images.

- Specifically, the main goals for calibration include:
  - Wavelength alignment and assignment
  - Converting from radiance values received at the sensor to reflectance values of the target surface

- Thus, the required calibration procedures are:
  - Wavelength calibration
  - Radiometric reflectance calibration
  - Spatial calibration
Wavelength Calibration of the HS System

- The purpose of wavelength calibration is to assign a discrete wavelength to the hyperspectral image band.
- This will enable data analysis and information extraction from the hyperspectral images in order to associate the correct wavelength to the observed target.
- Wavelength calibration is needed in the initial instrumentation stage when a hyperspectral imager is manufactured and tested.
- Re-calibration of the instrument is also necessary after several months or a year of significant operation of the sensor.
Wavelength Calibration of the HS System

- Wavelength calibration is accomplished by using a mercury-argon lamp.
- This light source produces known accurate spectral lines at fixed wavelengths.
- Image data of the calibration light are then collected and a spectral profile of different pixels in the image can be produced.
- The last step is to run a regression based on linear, quadratic, cubic or trigonometric equations.
Radiometric reflectance calibration

- This process involves a pixel-by-pixel calibration of the hyperspectral image data to percentage reflectance.
- The calibration can minimize or eliminate the inherent spatial non-uniformity in the artificial light intensity on the target area.
- In addition, the intensity of the artificial light source varies over time and the radiometric calibration process can compensate for such variations.
- The general approach includes collecting:
  - reference image
  - dark current image
  - sample images.
- The first precaution on this calibration process is to cool the imaging system to its initial operating temperature.
Reference image

- A white calibration tile made of a processed PTFE (Polytetrafluoroethylene) material is used for collecting the reference image.
- The material is hydrophobic, chemically inert, stable, and exhibits nearly Lambertian (perfectly diffuse) properties.
- Its reflectance is typically greater than 98% between 300 and 1700 nm.
- This consistent uniform reflectance enables proper conversion of samples images from at-sensor radiance to percent reflectance.
Dark current image

- Many hyperspectral imaging systems use CCD arrays for image acquisition.
- For such image sensors, there is an electronic current flowing in the detector arrays even without light shining on it.
- This current is called the electronic dark current or simply dark current.
- Thus, dark current is dependent on temperature.
- Dark current is also proportional to integration time.
- Dark current images are also taken before acquiring sample images.
Sample image and calibration

- When taking the sample images, the same integration time and imaging settings as used for acquiring the reference and dark images should be used.

- To convert raw digital counts of reflectance into percent reflectance the following equation is used:

\[
\text{Reflectance}_{\lambda} = \frac{S_{\lambda} - D_{\lambda}}{R_{\lambda} - D_{\lambda}} \times 100\%
\]

- where \( \text{Reflectance}_{\lambda} \) is the reflectance at wavelength \( \lambda \), \( S_{\lambda} \) is the sample intensity at wavelength \( \lambda \), \( D_{\lambda} \) is the dark intensity at wavelength \( \lambda \), and \( R_{\lambda} \) is the reference intensity at wavelength \( \lambda \).
Spatial calibration

- The resolution in the $x$ direction is determined by the combination of the working distance, lens, imaging spectrograph and camera.
- In line-scanning hyperspectral systems the spatial range for the $y$ direction is determined by the number of scans.
- For the calculation of the resolution in the $x$ direction, two different examples are presented.
- In these examples, the spatial resolution for the $x$ direction of the hypercube was determined by dividing the real spatial distance by the number of image pixels in this range.
- In the first one, a white paper printed with thin parallel lines 2mm apart was used.
- In the second one, a white paper printed with 2mm width parallel lines 10mm apart was used.
Spatial calibration – First example

- Specifically, there are 217 pixels within 62 mm spatial distance.
- Thus, the spatial resolution for the x direction is 0.29 mm/pixel.

![Image showing spatial resolution](image_url)
Spatial calibration – Second example

- Specifically, there are 569 pixels within 200 mm spatial distance.
- Thus, the spatial resolution for the x direction is 0.35 mm/pixel.
Hyperspectral imaging analyses

- Collection of a HS image by utilizing ideal acquisition conditions.
- Calibration: white and dark HS images.
- Extraction of the spectral data from the ROI that present different quality features.
- Preprocessing: to reduce noise, improve the resolution of overlapping data, etc.
- Qualitative analysis – multivariate analysis.
- Post-processing: segmentation, enhancement, morphological feature extraction.
Wavelength selection strategy

- There is no standard method to select the significant wavelength from the whole spectrum.
- A variety of strategies have used by different authors:
  - Analysis of spectral differences from the average spectrum
  - Stepwise regression
  - Principal component analysis (PCA)
  - Fisher discriminant analysis (FDA)
  - Independent component analysis
  - Partial least squares
Multispectral Images

- A multispectral image is a collection of several monochromes images of the same scene, acquired at specific frequencies across the electromagnetic spectrum.
- Each image is referred to as a band.
- The simplest and the most inexpensive implementation of a multispectral imaging system is the use of a rotatory disk called a filter wheel carrying a set of discrete bandpass filters.
- In this case, the spectral range and the resolution are determined by the number and the bandwidth of the filters that are housed in the wheels.
Multispectral Imaging Systems

- The main characteristic of the bandpass filters is that they transmit a particular wavelength with high efficiency while rejecting light energy out of the passband.
- As the filter wheel employs mechanical rotation, the light perpendicularly transmits across different filters, generating a series of narrow band images at different predetermined wavelengths.
- Interference filters are commonly used as optical bandpass filters.
- Central wavelength (i.e., wavelength corresponding to peak transmission) and spectral bandwidth that is defined as full width at half maximum (FWHM) are two key parameters for the bandpass filters.
Multispectral Imaging Systems

- Electronic filter wheels can be synchronized with the camera system to fulfill automatic filter switching and image acquisition. The filter wheels are easy to use and relatively inexpensive.

- The main disadvantage of using this configuration is the requirement for repetitive scanning of the same specimen at several wavelengths.

- Other limitations:
  - slow wavelength switching,
  - mechanical vibration from moving parts
  - image misregistration due to the filter movement
Multispectral Imaging Systems

- The more advanced way to filter light is to use tunable filters that can be controlled electrically.
- The main advantage of tunable filters is that they are very fast compared to filter wheels, improving the temporal resolution of the measurement.
- Tunable filters can be roughly divided into two categories
  - Acousto-optical tunable filter (AOTF)
  - Liquid crystal tunable filters (LCTF)
- Acousto-optic tunable filters (AOTF) and liquid crystal tunable filters (LCTF) operate on different principles, but they are both capable of rapid wavelength selection with microsecond to millisecond tuning speeds while preserving imaging integrity.
Multispectral Imaging Systems

- An AOTF is a diffraction based optical-band-pass-filter that can be rapidly tuned to pass various wavelengths of light by varying the frequency of an acoustic wave propagating through an anisotropic crystal medium.

- Wavelength switching for the AOTF is very fast (typically in tens of microseconds) owing to the fact that the tuning speed is only limited by the speed of the sound propagation in the crystal.
Important features of the AOTF include:

- high optical throughput
- moderate spectral resolution
- broad spectral range
- fast wavelength switching
- accessibility of random wavelength
- flexible controllability and programmability.
Multispectral Imaging Systems

- A liquid crystal tunable filter (LCTF) is a solid state instrument that uses electronically controlled liquid crystal cells to transmit light with a specific wavelength with the elimination of all other wavelengths.

- The LCTF is constructed from a series of optical stacks, each consisting of a combination of a birefringent retarder and a liquid crystal layer inserted between two parallel polarizers.
Multispectral Imaging Systems

- The liquid crystal cell is used in each stage to realize electronic tunability.
- An electric field is applied between the two polarizers which causes small retardance changes to the liquid crystal layer.
- The wavelength switching speed depends on the relaxation time of the liquid crystal as well as the number of stages in the filter.
- Typically, it takes tens of milliseconds to switch from one wavelength to another, which is far longer than the response time of the AOTFs.
Applications

- Traditionally, hyperspectral and multispectral imagery have been employed in earth remote sensing applications using aerial or satellite image data.
- More recently, low cost portable hyperspectral and multispectral sensing systems became available for new fields of applications.
- Agriculture is one of the most active research areas regarding analysis of hyperspectral and multispectral imagery.
Bruise detection of apples [Lu, R., 2003]

- The objective of this research was to investigate the potential of near–infrared (NIR) hyperspectral imaging for detecting bruises on apples in the spectral region between 900 nm and 1700 nm.
- An NIR hyperspectral imaging system was developed and a computer algorithm was created to detect both new and old bruises on apples.
- Experiments were conducted to acquire hyperspectral images from Red Delicious and Golden Delicious apples over a period of 47 days after bruising.
- Principal Component (PC) transform and Minimum Noise Fraction Transform (MNF) methods were applied to detect bruises areas.
Bruise detection of apples [Lu, R., 2003]

- For each raw image, multiplication of the first and third PC images was performed.
- In the resultant image, the bruises would always appear to be darker than normal tissue.
- Bruises were normally present in the third MNF image, either dark or bright. Either group could be a candidate for bruises.
Bruise detection of apples [Lu, R., 2003]

- Results showed that the spectral region between 1000 nm and 1340 nm was most appropriate for bruise detection.
- Bruise features changed over time from lower reflectance to higher reflectance, and the rate of the change varied with fruit and variety.
- Using both principal component and minimum noise fraction transforms, the system was able to detect both new and old bruises, with a correct detection rate from 62% to 88% for Red Delicious and from 59% to 94% for Golden Delicious.
Supervised Multivariate Analysis of Hyperspectral NIR Images to Evaluate the Starch Index of Apples [Menesatti, P., 2008]

- Spectral images of 88 Golden Delicious Klon B apples were sampled at seven different maturity stages.
- Partial least-squares discriminant analysis (PLSDA) technique was used on hyperspectral NIR images to classify single pixels in two classes (starch and starch-free).
- The mean classification error rate obtained through PLSDA was 19.19%.
PCA and FLD on Hyperspectral Image Feature Extraction for Cucumber Damage Inspection [Cheng, X., 2004]

- PCA and Fisher’s Linear Discriminant (FLD) method are combined for a better detection of cucumber chilling injuries.
- The PCs preserved the most energy of the original data, and provided good performance in recognizing obviously separated classes.
- FLD analysis contributed to classifying similar patterned classes.
- The integrated method outperforms the PCA and FLD methods when they are used separately for classifications.
Hyperspectral waveband selection for internal defect detection of cucumbers and whole pickles [Ariana, D. P., 2010]

- The objective was to select important wavebands for further development of an online inspection system to detect internal defect in pickling cucumbers and whole pickles.

- Hyperspectral images were acquired in the range of 400–1000 nm.

- Up to four-waveband subsets were determined by a branch and bound algorithm combined with the k-nearest neighbor classifier.

- The highest classification accuracies of 94.7 and 82.9% were achieved using the optimal four-waveband sets of 745, 805, 965, and 985 nm at 20 nm spectral resolution for cucumbers and of 745, 765, 885, and 965 nm at 40 nm spectral resolution for whole pickles, respectively.
Vis/NIR Hyperspectral Imaging for detection of hidden bruises on Kiwifruits [Lü, Q. 2011]

- In this case, bruises are not visible externally because of the special physical properties of the kiwipeel. Hyperspectral imaging technique is utilised to inspect the hidden bruises.

- Five optimal wavelengths are selected using PCA: 682, 723, 744, 810 and 852nm.

- Bruises regions were segmented using SVM based on the PCA images.

- The error of hidden bruises detection on fruits was 12.5%.
References

Thank you very much!