The Society for engineering in agricultural, food, and biological systems

Paper Number: 01-1105
UILU Number: 2001-7010
An ASAE Meeting Presentation

Hyperspectral Imaging System Optimization and Image Processing

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Written for presentation at the
2001 ASAE Annual International Meeting
Sponsored by ASAE
Sacramento Convention Center
Sacramento, California, USA
July 30-August 1, 2001

Abstract. *In the research of remote sensing for precision farming applications, the data quality of the aerial hyperspectral imaging system suffers from geometric distortions. Some of the distortions are caused by aircraft attitude change during the current pushbroom type image scanning. These distortions must be corrected before image data can be geo-referenced and used for field pattern identifications. Development of methods and algorithms for the correction of this type of remote sensing data distortion is the objective of this study. Three different approaches, namely manual correction, sensor augmentation, and image processing were developed. A Fiber Optic Gyroscope (FOG) attitude sensor was used on board the airplane to measure the real-time image sensor attitude, a polynomial interpolation algorithm was developed, and a reference straight feature was segmented based on the selected training dataset. The performance of all three methods was evaluated and compared. It is suggested that further integration of the attitude sensor with the imaging system can provide an instantaneous fully automated distortion correction system.*

Keywords. Geometric distortion correction, hyperspectral image, attitude.

Introduction

Precision agriculture describes the efforts of dealing with the variability of the agricultural field. By carefully identifying the infield variability, farmers can find a balance between production maximization and environmental stress reduction. There are many approaches for the collection of field data for precision farming. Remote sensing has been proven to be a fast way for high-density data collection and has many applications in agriculture (Senay et. al, 1998). These applications include crop protection (Hatfield and Pinter, 1993), yield modeling (Gopalapillai and Tian, 1999), nitrogen stress detection (Bausch and Duke, 1996), irrigation management (Coloaizzi et. al, 2000), and weed mapping (Brown et. al, 1994), etc. Traditionally, remote sensing images were divided into two major categories, including satellite-based images and airborne-based images. Satellite images normally cover large areas, with relatively fixed time interval and large spatial resolutions. Airborne images normally cover small areas, with flexible flight schedules and high spatial resolutions.

Typically, agricultural remote sensing uses broadband multispectral images and has a spectral range from visible to near infrared. Thanks to NASA's remote sensing commercialization program, more aerial hyperspectral images are available for using in agricultural remote sensing. A hyperspectral image has more bands (tens to hundreds) with narrow bandwidth (one to several nanometers) in the same spectral range as a multispectral image. Due to the high data volume of a hyperspectral image, it is expected that more detailed information can be extracted from the image. Resources required for handling such images also increase rapidly compared with multispectral images. These resources include personnel, computation power, storage devices, and a high-speed network.

The aerial hyperspectral imaging system used by Spectral Vision Midwest (a NASA regional contractor) is a pushbroom prism-grating scanner. For a pushbroom sensor, pixels in cross-track rows are scanned one line at a time while the aircraft flys over the field (Schowengerdt, 1997). The hyperspectral bands are created by a 2-D detector array. For each scanned line, a prism disperses the optical beam over wavelength. The dispersed beam is along the in-track direction and is captured by the 2-D detector array. Because of the above nature of the pushbroom sensor, its image acquisition time is different from a multispectral digital camera, which acquires an image in one shot. For a 750 pixel by 2500 pixel hyperspectral image with 120 bands, it requires up to one minute to scan. During this period, the pilot must keep the airplane as stable as possible. There are many factors, such as air turbulence and wind disturbance, contribute to the aircraft's instability. To compensate for the aircraft attitude change, the whole imaging system must be mounted on a stabilized platform. However, aircraft disturbance cannot be isolated completely. The aircraft attitude changes, which cause scanning off-nadir scene, will eventually affect the resulting image. As a consequence, distortion would be created in the image, especially in the in-track direction due to aircraft roll movement.

Pushbroom sensors are used on both aerial and satellite imaging systems. For successful image processing, the geometric distortion due to vehicle attitude change must be corrected in the pre-processing phase. This is especially true when doing agricultural remote sensing projects, which require high spatial resolution aerial images and need pixel level data. It is also important in doing multi-temporal data analysis with data collected from different dates. There are many different ways to correct for distortion and are generally divided into three approaches. The first method, a manual approach, corrects the distortion through human judgment and is straightforward. The second approach is vehicle modeling and sensor augmentation. The third approach is through image processing.

Obviously, people can locate the image distortion directly. The manual method thus involves the following steps. First, it requires finding an original straight feature (i.e., a local highway) on the image based on a reference image. The straight feature is then digitized through an interactive computer program. By matching the digitized data and the reference straight feature, image distortion can be subsequently corrected. Although this approach is widely used, it has many drawbacks. Quality of the resulting image depends on the skills of the operators. It is subjected to human errors and is quite time consuming. Further, the interpolation method used in the correction step also has an influence on the final image quality. There is a discontinuity in the digitized points when using the local interpolation method (Press, et al, 1992) due to interpolation schema switch. Its effect is the teeth edge on the resulting images.

In the second approach, which is a sensor and modeling based method, the distortion is calculated through modeling or direct sensor measurements. For the satellite systems, the modeling procedure was mostly used. When doing modeling, ground control points (GCPs), orbital models, and earth shape were used (Huseby et. al, 1999, Moreno and Melia, 1993, Shin et. al, 1997, Toutin and Carbonneau, 1992). For the aerial imaging system, the situation is much more complicated because the airplane is subjected to more influential factors. It is difficult to model airplane movement. Two proposed pushbroom type aerial hyperspectral systems suggested the use of aircraft attitude data (Makisara et. al, 1994, Schaepman et. al, 2000). However, details on how to collect and use this data were not given.

Image processing, the third approach for geometric distortion correction, focuses on automatic correction through appropriate image processing techniques, ground control points (GCPs), reference images, and matching techniques. Zhang et. al (1997) and Shin et. al (1997) used coastline detection and had satisfactory results.

When the remote sensing project is well under way at the Illinois Laboratory for Agricultural Remote Sensing (ILARS) at the University of Illinois at Urbana Champaign (UIUC), hyperspectral images with regular time intervals will come from Spectral Vision Midwest. The first job for image processing is to remove the aforementioned geometric distortion. Because there is no software commercially available for this work, the Lab has to develop its own. For a quick start, a program written using the manual approach had satisfactory results. However, due to the above drawbacks of this approach, it is necessary to develop other distortion correction methods. This paper presents different approaches regarding this problem.

OBJECTIVES

When the hyperspectral image is acquired from a pushbroom type image scanner, the scanner platform attitude changes will cause geometric distortion to the image. The objective of this study is to develop methods and algorithms for the correction of such geometric distortions. These correction methods include three different approaches: manual, sensor augmentation, and image processing.

INSTRUMENTATION AND PROCEDURES

All the flights were conducted by Precision Aviation (Rantoul, IL) using fixed wing aircrafts. The hyperspectral image sensor was RDACS/H-3, which is a prism-grating pushbroom scanner developed by NASA. Spectral resolution for the 120-band image was 3 nm (473 to 827 nm), with spatial resolution of 1 or 2 m.

A series of images taken in the summer of 2000 were used in this study. Images were typically taken on sunny days with clear skies close to noon. Clouds were not apparent in the acquired images. Atmospheric effects were minimal due to the low flight altitude. All image data were raw data without any preprocessing.

Both manual and image processing approaches need accurate ground truth information, i.e., an identifiable straight feature. It was found that for this application, the USGS 2-meter resolution aerial image is a good source. The USGS aerial image can be obtained publicly from the online Microsoft TerraServer (Microsoft Corp. 2001)

Figure 1 describes the procedure for the manual correction method. The image used was taken on July 9, 2000. The target area was the Agricultural Engineering Research Farm at UIUC. The flight direction was west-to-east, with an altitude of 4000 ft, and spatial resolution of 1 m. A straight road (Curtis Road) in west-east direction was identified from the referenced image. The manual correction method was implemented in associated with ENVI (Research System Inc, 2000). After digitizing the corresponding distorted road, a polynomial interpolation algorithm was used to do the correction. Generally, this process may be carried out for several times until a satisfactory result is obtained.

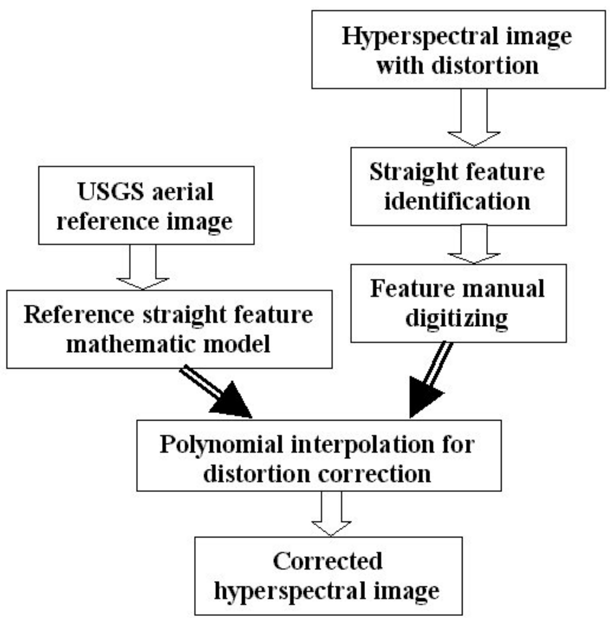


Figure 1. Manual correction approach

The sensor augmentation approach used the aircraft attitude information, especially the aircraft roll angle. Aircraft attitude angles are defined in Figure 2. The definition used a right-handed coordinate system. For a right-handed coordinate system, any attitude vector can be defined by the cross product of the other two attitude vectors.

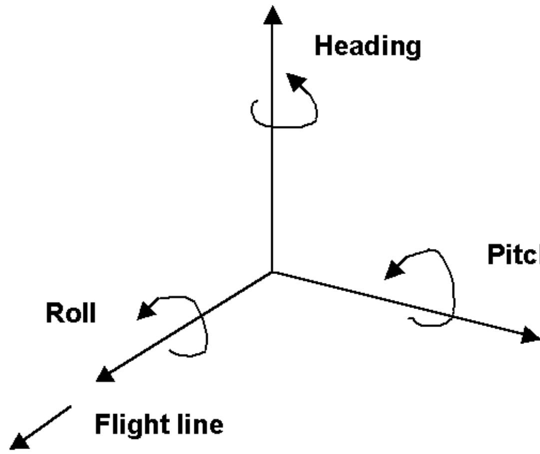


Figure 2. Aircraft attitude definition for the sensor augmentation method.

Figure 3 is the procedure for the sensor augmentation method. An attitude sensor was used in this approach to measure the imaging scanner angles. The attitude sensor was a JCS-7401GA Fiber Optical Gyro (FOG) attitude measurement device (Japan Aviation Electronics). The FOG sensor can output real time vehicle attitude at a maximum rate of 50 Hz. It has the capability of outputting both analog and digital signals. These signals include: roll, pitch, heading and six-degree accelerations. For this application, the digital output through RS232 serial communication was used. The sampling rate from the computer was set to 25Hz. However, the actual attitude-reading rate was 19-22 Hz. The FOG sensor was mounted on the gyro stabilization platform built for the hyperspectral image scanner and along the platform's centerline. Figure 4 shows the airplane and its mounting position.

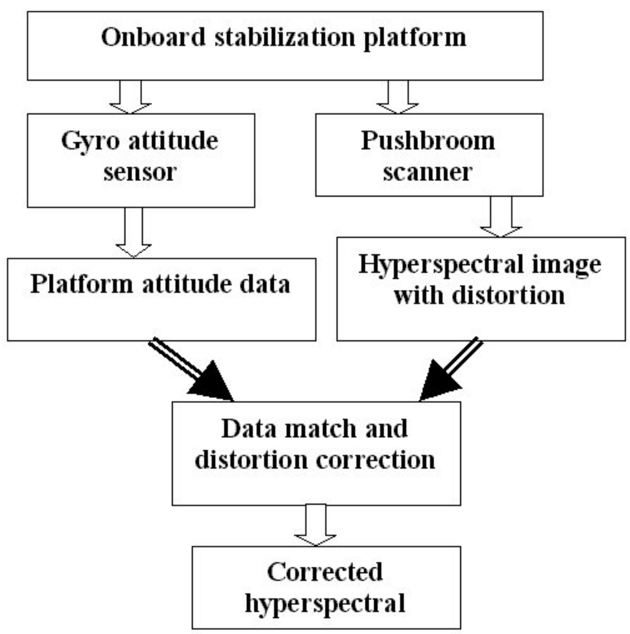


Figure 3. Sensor augmentation correction approach.

A laptop computer was used to collect data output from the FOG sensor. Attitude angles of the gyro platform were recorded (with time stamp) at the same time as the image was scanning. The two sets of data were processed later in the Lab. Image distortion was corrected after sensor attitude was computed for each scan line. In this paper, only the roll angle was used to make the correction. The flight was on August 31, 2000, near the intersection of Windsor Road and Neil Street in Champaign, IL. The image shows most of the flight along Windsor Road, which runs in a west-east direction. Flight height was 7500 ft. Its spatial resolution was 2 m.

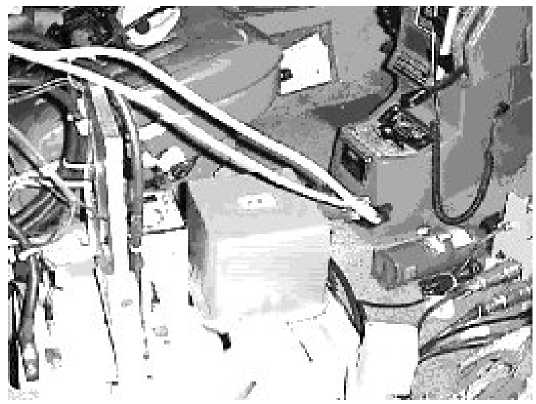



Figure 4. Airplane (left) hosting hyperspectral image scanner and the FOG attitude sensor mounted (right) on the gyro platform.

Due to the drift feature of the Gyro sensor, attitude measurement is changing gradually even though the sensor is under static conditions. To calibrate the drift, attitude data for both takeoff and landing, while the plane was idle on a leveled runway, was recorded. These two sets of data were used to compute drift value for any attitude reading during image acquisition.

For each scan line, its correction value was computed based on equation 1

$$N\_shift = \frac{flight\_height \times \tan(roll\_angle)}{GIFOV} \tag{1}$$

where *N_shift* is the number of pixels needing to be shifted along a scan line to correct the distortion. *Flight_height* is the airplane's flight height during data acquisition. *GIFOV* is the ground instantaneous field of view, which can be viewed as the image pixel resolution. *Roll_angle* is the roll angle for the corresponded scan line.

The image processing approach is basically a feature extraction and classification procedure. Figure 5 is the procedure used for the image processing method. Similar to the manual method, the goal of the image processing method is also to identify a straight feature within the image. For a carefully selected straight feature, both its spectral and spatial signatures are distinct from other background signatures. Based on the above spectral and spatial information, straight features can be segmented and spatially located with the distortion subsequently corrected.

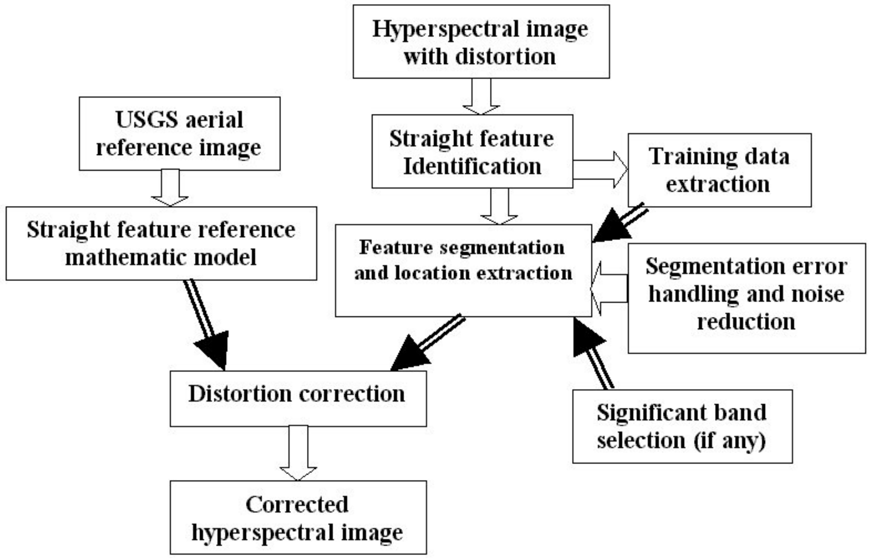


Figure 5. Image processing correction approach

For this method, the image was taken on May 2, 2000. The target area was the UIUC Research Farm. The flight direction was west-to-east and its altitude was 4000 ft., with a spatial resolution of 1 m. The same paved highway (Curtis Road) used for the manual method was identified from both the USGS aerial image and the hyperspectral image. Pixels along the highway were distorted. Training data were the highway cross-section pixels. Reflectance values from the training pixels were averaged to generate a single cross-section training signature.

Feature segmentation was carried out as follow. A line segment with the same length as the training data segment was selected from an image row. A score was computed for this selected line segment to evaluate its match with the training data. In this study, the score was the sum of squares of the residuals between the training data and the selected working line segment (equation 2).

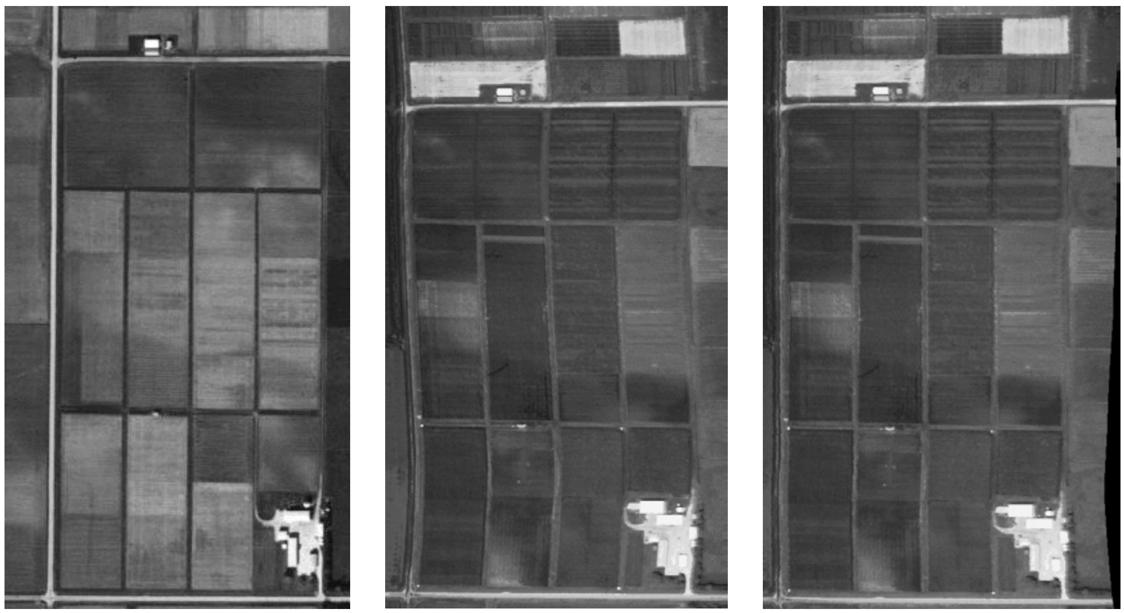
$$score = \sum_{i=1}^{n} \left[train(i) - data(i) \right]^2 \tag{2}$$

where *i* is the band index, *n* is the total number of selected bands, *train* is the training data set, and *data* is the selected line segment. As the line segment moved one pixel after one pixel along the row, a *score* number can be computed for each pixel location. The pixel location with the lowest *score* was selected as the highway center position.

The above segmentation process produced many errors. A noise remove module was applied to the segmented data and some ancillary information was used to help correct segmentation of the straight feature. One example of ancillary information was the pushbroom sensor itself. Due to the slow attitude movement of the sensor platform, neighboring pixels must be connected in a continuous way. Segmentations with abrupt changes between neighboring pixels can be viewed as error segmentation and need to be take into consideration. A low pass filter of window size 8 was also used to further smooth the segmented result. Once the road center is located, the image distortion can be subsequently corrected.

RESULTS AND DISCUSSION

Figure 6 is the manual correction result with first order polynomial interpolation (linear). It can be observed from the images that if there is an identifiable straight feature and the distortion is not severe, the distortion due to aircraft roll movement can be corrected. However, quality of the result is directly related to human judgment. If the digitizing interval is too large, a teeth edge effect can be observed from the corrected image. To smooth the image edge, a higher order polynomial interpolation method is desired in the correction algorithm.



a b c

Figure 6. Results of the manual correction method (linear interpolation). a. USGS aerial photo with 2-meter resolution. b. raw hyperspectral image. c. manual corrected image. The paved highway on the left side of the image was used as the reference straight feature.

To correctly compute sensor attitude, the gyro sensor drift must be taken into consideration and calibrated. Figure 7 shows the takeoff and landing roll data, which can be used to compute sensor drift. The results show that, for a three-hour flight, the FOG sensor generated ~ -1° drift. Under the assumption that the drift occurred linearly with time, drift angle at any time during the flight can be simulated.

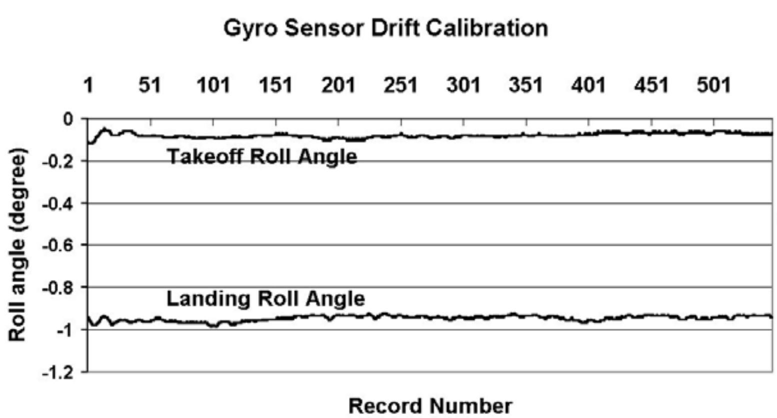


Figure 7. Takeoff and landing roll angle for sensor drift calibration.

Figure 8 shows the recorded gyro platform roll angle during image acquisition. The data is similar to a cosine wave and changes gradually between –1.3° to + 1.3°.

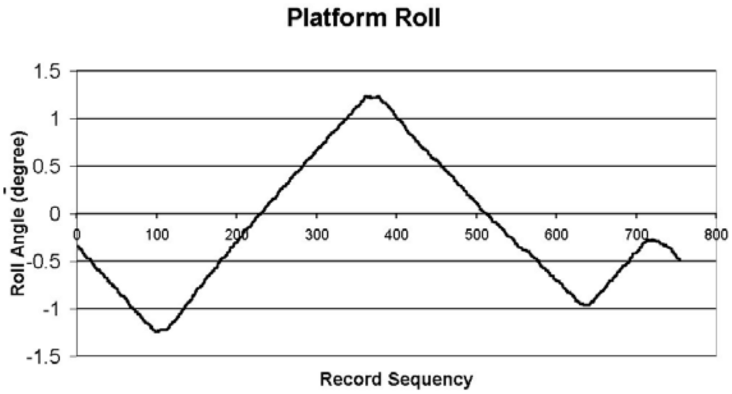
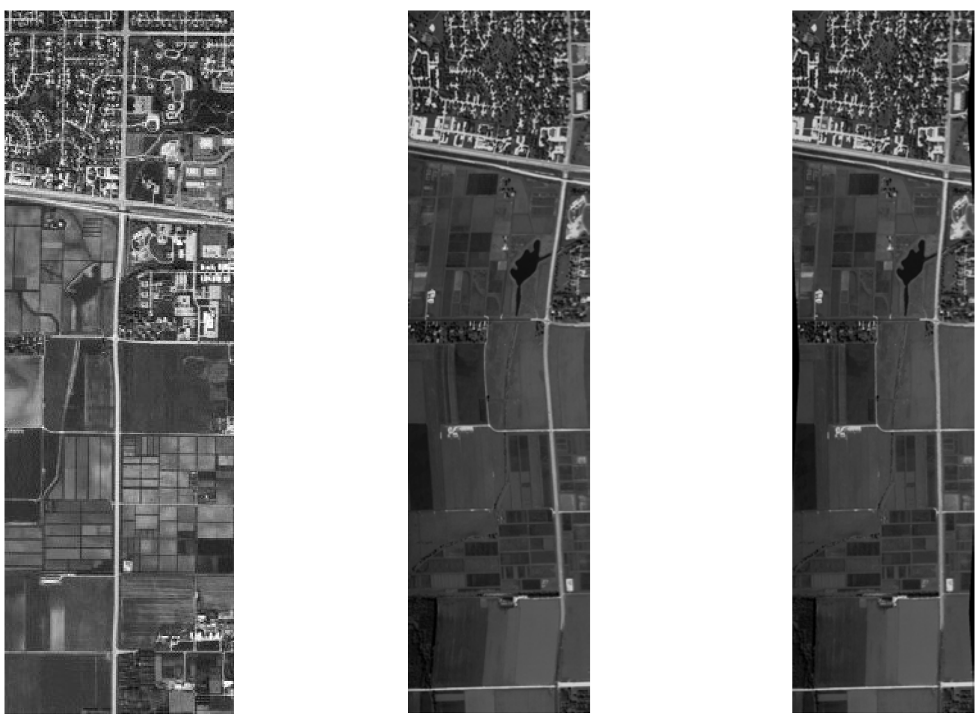


Figure 8. Sensor platform roll angle during data acquisition.

Figure 9 shows the processed images using the sensor augmentation method. In the middle of the reference image, there is a curve along Windsor Road. Under this circumstance, it would be very difficult to correct the distortion with the manual method. The sensor augmentation approach can recover this curve. This proved that if the roll data were processed properly, image distortion could be largely corrected.



a b c

Figure 9. Results of the sensor augmentation correction method. a. USGS aerial photo with 2-meter resolution. b. raw hyperspectral image. c. corrected image. Note the paved highway has a curve, which makes it difficult to be corrected by the manual approach.

Although the above sensor augmentation method provides satisfactory results, there are still some problems with this method. Because the two data sets were not collected in a pure synchronous way, it is necessary to shift the attitude data to fit the exact scan line location. This indicates that the results are not yet optimized. The best way to implement this method is to combine the image acquisition and attitude acquisition. In this way, each scan line would have an accurate attitude reading.

Aircraft pitch angle also plays an important role in image distortion. Problems associated with it include over-sampling, which re-scans line(s) that have been scanned, and under-sampling, which misses scan line(s) that have not been scanned. In this paper, distortion due to pitch movement was not taken into consideration. It can be expected that image quality would be improved if this information were used.

Figure 10 depicts the results from the image processing approach. The reference image is the same as the manual method. It can be seen that this method produced satisfactory correction results. Compared with the manual method, which involves considerable input from the operator, this method needs much less input from the operator.

a b c

Figure 10. Results of the image processing correction method. a. USGS aerial photo with a 2-meter resolution. b. raw hyperspectral image. c. corrected image. The paved highway on the left side was used as the reference straight feature. The processing used all 120 bands.

Because the segmentation algorithm is based on the selected road cross-section training data, training data selection is crucial. The selected paved road had a relatively uniform signature compared with its background. This is because the processing algorithm needs stable feature reflectance and constant feature texture. The road width was almost fixed which provided easy feature match and extraction.

It was found that if the road signature changed, the segmentation accuracy also decreased. Large signature change could cause erroneous segmentation. To reduce this error, the algorithm enabled tolerance over segmentation results, which used a threshold to determine if it was a correct segmentation (the threshold was a test-and-try result). Keeping track of the last successful segmentation also provided a way back to the correct segmentation location after error occurred. In the detection process, a segmentation error handling and noise reduction module was implemented to do the above works.

The above image processing method used the spatial and texture information implicitly when picking one line segments at a time for road detection. The pixel average approach blanked out any texture information within the crossroad line segment. To use the spatial and texture information explicitly, the spatial relationships among pixels within the road cross-section segment must be considered. It is also desirable to extract the most significant bands for road detection. In this way, some band-related noise in the segmentation could be minimized. Computer resources could also be saved if fewer bands were used. However, how to effectively extract the most significant bands remains a question that warrants further investigation.

Conclusion

Different methods for the correction of geometric distortion of aerial hyperspectral image were investigated in this paper. These methods include a manual approach, a sensor augmentation approach, and an image processing approach. All three methods offered satisfactory results with certain restrictions. For the manual method, an identifiable straight feature is required. The final correction quality is based on human inputs and is the most time consuming approach of the three methods. For the sensor augmentation method, effort is needed to combine both the image data acquisition and attitude data acquisition. This approach suffers from synchronization problems between the two data sets. It is expected that the sensor augmentation method would produce the best results among the three methods if it would be able to integrate the attitude sensor into the imaging system. For the image processing method, an identifiable straight feature is also required. For the straight feature, the spectral signature and spatial texture must be distributed in a distinct way. Such distributions would enable fast and accurate road segmentation. Extracting of most significant bands for fast and efficient road segmentation is expected in the future study.

Acknowledgements

This research has been supported by the Illinois Council of Food and Agricultural Research (C-FAR), project number IDACF 01-DS-3-1 AE and the University of Illinois. The use of trade names is only intended to provide specific information to the reader, and does not constitute endorsement by the University of Illinois. The authors also would like to thank Spectral Vision Midwest for coordinating flights and providing images, and Precision Aviation for data collection.

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