DEVELOPMENT OF AN AIRBORNE REMOTE SENSING SYSTEM FOR AERIAL APPLICATORS

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ABSTRACT

An airborne remote sensing system was developed and tested for recording aerial images of field crops, which were analyzed for variations of crop health or pest infestation. The multicomponent system consists of a multi-spectral camera system, a camera control system, and a radiometer for normalizing images. To overcome the difficulties currently associated with correlating imagery data with what is actually occurring on the ground (a process known as ground truthing); a hyperspectral reflectance instrument was integrated into the image processing system. A GreenSeeker 505 Handheld Optical Sensor was mounted on a John Deere 4710 sprayer with a 30 meter swath and used to map the field. Data from the handheld optical sensor were georeferenced and converted to NDVI. This data was imported into Farm Works software and classified based on NDVI values. The data was then smoothed using the inverse distance subroutine and prescription maps were generated for each of the remote sensing methods. Good correlation was obtained between the aerially-acquired images and the GreenSeeker data. Irradiance data measured from a radiometer were used to normalize imagery. Traditionally, several large standardized reflectance panels have been used for this purpose. A less cumbersome approach is to use radiometers to record solar irradiance which is then used to convert recorded solar irradiance and images to milliwatts per square centimeter of energy. The data were imported into software and prescription maps were produced. This system is able to provide aerial applicators remote sensing service and prescription mapping of fields.

Keywords: Remote sensing, GPS/GIS, precision agriculture, aerial application, crop management

INTRODUCTION[1]

Remote Sensing along with Global Positioning Systems (GPS), Geographic Information Systems (GIS), and variable rate technology (VRT) has been developed for scientists to implement to help farmers maximize the economic and environmental benefits of crop pest management through precision agriculture. Remote sensing has been conducted by satellites, aircraft, or ground-based platforms. Satellite remote sensing is appropriate for large-scale studies but often can not meet the spatial resolution requirement of many applications. Ground-based platforms, such as handheld spectroradiometers, are typically used for ground truth measurements. Airborne remote sensing is flexible and able to achieve different spatial resolutions with different flight altitudes.

In airborne remote sensing for agricultural research and applications the use of hyperspectral sensors has been steadily increasing in the last decade. Even so, the airborne multispectral technique is still a good source of crop, soil, or ground cover information. Multispectral systems are much less expensive and data intensive compared to hyperspectral systems. They are a cost-effective option in many cases. In pest management, detection of insect damage to crops along with weed infestation and crop disease provides valuable information for management planning and decision. Airborne remote sensing has been widely used in detection and analysis of pest damage in fields. Weed detection has probably been the most successful application of airborne remote sensing in pest management. In recent years, there has been a shift away from uniform, early season weed control towards using herbicide-ready crops and applying post-emergence herbicide only as needed. This strategy change has generated increased interest in using remote sensing to define the extent of weed patches within fields so they can be targeted with variable rate ground and aerial spray rigs (Pinter et al., 2003). Richardson et al. (1985) demonstrated that multispectral aerial video images could be used to distinguish uniform plots of Johnsongrass and pigweed from sorghum, cotton, and cantaloupe plots. By comparing visual assessment of herbicide injury in cotton with CIR (Color-Infrared) photography, NIR (Near InfraRed) videography, and wideband handheld radiometer, Hickman et al. (1991) concluded that remote sensing and mapping of moderate herbicide damage was not only possible, but that the application rate of herbicides could be estimated. Medlin et al. (2000) evaluated the accuracy of classified airborne CIR imagery for detecting weed infestation levels during early-season *Glycine max* production. Ye et al. (2007) used airborne multispectral imagery to discriminate and map weed infestations in a citrus orchard. There have been a number of successful applications of airborne remote sensing in detecting insect infestations

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[1] Mention of trademark, vendor, or proprietary product does not constitute a guarantee or warranty of the product by the USDA and does not imply its approval to the exclusion of other products that may also be suitable.

for pest management. Hart and Myers (1968) used aerial CIR photography to detect insect infestation on trees in a number of citrus orchards. Aerial CIR film and multispectral videography have been also used to detect citrus blackfly and brown soft scale problems in citrus as well as whitefly infestations in cotton (Hart et al., 1973; Everitt et al., 1991; Everitt et al., 1994; Everitt et al., 1996). Airborne remote sensing technology has been employed for detecting crop disease and assessing its impact on productivity (Heald et al., 1972; Henneberry et al., 1979; Schneider and Safir, 1975; Cook et al., 1999; Yang et al., 2005).

For agricultural applications two different airborne multispectral imaging systems have been mainly developed and used: video system and camera system. The camera systems were typically built with several cameras lined up together and each of the cameras with a specific filter lens takes care of imaging in a specific band, such as blue band, green band, red band, near-infrared (NIR) band, and even thermal band. This typically had the problem of misalignment of the images from different bands. Multispectral cameras produce and line up the images from the different bands with the built-in devices and the data can be worked on the composite image or the image from an individual band. MS4100 (Geospatial Systems, Inc.,West Henrietta, NY) is a such a multispectral cameras. Conventionally, the operation of the camera needed a technician on the aircraft to control the actions of the camera. This caused the problem of manual operation without control of roll, pitch, and yaw camera stabilization. Automation is necessary for the multispectral camera system in order to reduce the labor and maintain the consistency of the system operation. Based on the needs in agricultural research and applications, a camera control system, TerraHawk (TerraVerde Technologies, Inc.,Stillwater, OK) was prototyped to specifically automate the operation of the MS4100 multispectral camera and to control roll, pitch, and yaw camera stabilization during the flight. The objective of this paper was to describe the automated airborne multispectral imaging system with the integration of the MS4100 camera and the camera control system and to describe image processing with sample imagery to demonstrate the capability and the potential of the system for crop pest management.

SYSTEM DESCRIPTION

MS4100 multispectral camera

MS4100 is currently a GSI (Geospatial Systems, Inc.) product, formerly Duncan Tech's. It is a multispectral HDTV (High Definition Television) format 3CCD (Charge-Coupled Device) color/CIR (Color-Infrared) digital camera. This camera is a straight upgrade of Duncan Tech 3100 and 2100.

The MS4100 high-resolution 3-CCD camera provides the ultimate in digital imaging quality with 1920 (horizontal) x 1080 (vertical) pixel array per sensor and wide field of view of 60 degrees with 14 mm, f/2.8 lens. Color-separating optics work in concert with large-format progressive scan CCD sensors to maximize resolution, dynamic range, and field of view. The MS4100 is available in two spectral configurations: RGB (Red Green Blue) for high quality color imaging and CIR for multispectral applications. It images the four spectral bands from 400 to 1000 nm. It acquires separate red, green, and blue image planes and provides composite color images and individual color plane images. It also acquires and provides composite and individual plane images from red, green and NIR bands that approximate Landsat satellite (NASA, Washington DC and USGS, Reston, VA) bands. MS4100 is able to further provide RGB and CIR images at the same time and other custom spectral configurations (table 1). Note that if you run the RGB or CIR configuration individually, a base configuration will support any three-tap configuration running at 8 bits per color plane (i.e. 24 bit RGB). Adding a fourth 8 bit tap or outputting 10 bits per color plane will require the additional use of port with a second cable.

Table 1. MS4100 Spectral Configurations

RGB	red, green, and blue – color imaging
CIR	red, green, and NIR – color infrared imaging
RGB/CIR	RGB and CIR in a single camera
Multispectral	Custom spectral configuration to customer specifications

MS4100 camera configures the digital output of image data with CameraLink standard or parallel digital data in either EIA-644 or RS-422 differential format. MS4100 camera works with NI IMAQ PCI-1424/1428 framegrabber (National Instruments, Austin, Texas). With the software DTControl-FG (Geospatial Systems, Inc.,West Henrietta, NY) and the CameraLink configuration, the camera system acquires images from the framegrabber directly from within the DTControl program.

Camera control system

Image acquisition of MS4100 camera occurs in four different modes. Three of the modes require an external trigger signal to initiate a new acquisition. Free run mode requires no external control signals and provides high frame rates by overlapping the readout time with the exposure time. In this mode a technician can directly operate the camera through the DTControl software on the aircraft. However, this manual operation caused problems with lack of control of roll, pitch, and yaw camera stabilization during the flight. In order to reduce the labor and maintain the consistency of the image acquisition operation, automation is necessary for the camera system. For the purpose, a camera control system was prototyped specifically for aerial imaging using the MS4100 multispectral camera for integration of camera control computer and software, GIS-based flight navigation software, and GPS-based camera triggering for camera automation and automatic control of roll, pitch, and yaw camera stabilization during the flight (figure 1).

In the camera control system, a gimbal is provided for camera mounting for autonomous compensation of roll, pitch, and yaw. The gimbal maintains camera position at or near vertical nadir view and corrects for aircraft yaw by aligning the camera with the GPS heading. The camera is mounted in the gimbal by use of a secure, quick-release lock. Vertical positioning allows optimal placement of the camera within the fuselage port, even placing the camera several inches below the gimbal if needed. The gimbal axis is located near the base to minimize side to side displacement of the camera due to the gimbal operation when the camera is placed well into a port. After use, the camera easily detaches from the gimbal for protected storage.

A (8.4 in, 2.1 lb) touch pad was provided to interface the system control computer. The computer uses a small industrial mother board. It was selected primarily for its small size, low power requirement, and its PCI slot interface. An onboard PCI slot is required for the most advantageous use of the NI IMAQ 1424/1428 board. The fastest processor available is used for this board configuration, 512MB of memory, and a 20 GB mobile hard drive for data transfer between the camera control system and desktop computers. The touch pad is a sunlight readable LCD display that can be strapped to the pilot's leg as a knee board. It offers a resolution of 800 X 600 and allows user input by either a touch screen or a stylus pen.

With the gimbal, MS4100 camera, control computer, touch pad and system integration box containing a GPS unit, the camera control system was assembled (figure 2). Navigation and control software was used to operate the camera control system. The software displays a moving map that gives the current aircraft location relative to the fields that need to be imaged. It automates image acquisition by automatically triggering the camera to start taking images at a preset interval once the plane crosses the field boundary. Images can also be taken at any time by pressing the manual image button. The field boundaries are defined by GIS shape files, which are selected during the flight setup. A GPS track can also be displayed and saved showing the path the plane flew for future reference. The software also manages file directories, and transfers files to the removable device for post flight data retrieval when exiting the software. Besides in-flight navigation and control the software supports in-flight imaging simulation as well. During the flight the camera is triggered by GPS location. The auto control feature optimizes camera settings.

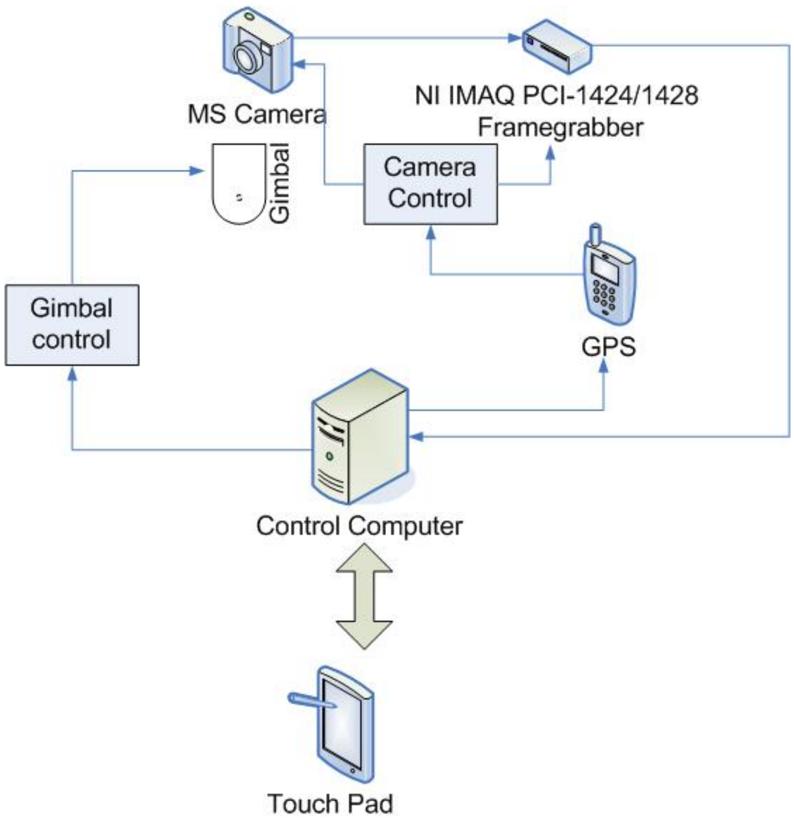


Figure 1. MS4100 camera control system structure.

Figure 2. Complete camera control system assemble.

Irradiance sensor

In order to compare the images acquired at different times the digital numbers of the images need to be normalized to percent of reflectance. For the normalization a radiometer is used to record solar irradiance. An irradiance radiometer is equipped to record the Sun's irradiance in the field to normalize images, as shown in figure 3. The procedure of the camera control system for image normalization was developed based on the Schiebe method named after Dr. Frank R. Schiebe, a USDA ARS senior scientist, who established the method for the use of radiometers and instrument calibration to provide an efficient and practical means to acquire reflectance images without the conventional standard reflectance panels.

Figure 3. An irradiance radiometer was used to record Sun's irradiance in the field.

Merging radiance images and solar irradiance data is the final step to calculate true reflectance images. The image correction software performs this reflectance calculation and generates the corresponding reflectance images.

NDVI Sensor

The GreenSeeker Hand Held Data Collection and Mapping Unit (NTech Industries, Inc., Ukiah, Ca.) is an advanced tool in precision agriculture technology for providing useful data to monitor the growth status of crops (figure 4). The GreenSeeker measures incident and reflected light from plants and outputs both NDVI and Red to Near Infrared Ratios. The sensor head is adjustable in 15 degree increments and mounted on an adjusted-length pole to set the sensor parallel to the target canopy. The control box supplies power to the sensor and external connectors. The GreenSeeker is equipped with a Hewlett Packard iPAQ pocket PC and specific software for data collection. Reflectance data from the sensor is captured and saved to a text file on the pocket PC. NDVI readings are shown immediately.

The sensor uses light emitting diodes (LEDs) to generate its own red and near infrared (NIR) light. Therefore, measurement can be taken at any time and under any light condition, day or night. The field of view is approximately constant for heights between 32 to 48 inches over the crop canopy and the width of the sensor measurement also is a constant 24 inches.

Figure 4. GreenSeeker Model 505 Handheld Optical Sensor Mounted on John Deere 4710 Variable-Rate Sprayer with 90’ Swath for Ground-Mapping NDVI in Cotton Field.

Unlike aerial and satellite imagery, the ground-based GreenSeeker sensor provides real-time data, which can be used to make variable-rate applications and map crop health and vigor. Cotton growers use the GreenSeeker to make real-time variable-rate applications of nitrogen, plant growth regulators and defoliants. A farmer in Oklahoma has been using GreenSeeker for three years on wheat. He used the GreenSeeker hand held unit along with nitrogen ramps to figure out mid-season N needs. They lowered their nitrogen expenses by over $6000.00 on a 4000 acre farm in a two year period.

Hyper Spectroradiometer

Spectroradiometers are used to measure plant reflectance and identify plant stress. Crop conditions can be closely monitored by using reflectance spectral imagery. FieldSpec® Handheld is an ideal portable field hyper spectral radiometer (FieldSpec®, Analytical Spectral Devices, Inc) (figure 5) for applications in precision agriculture. The hyper spectral radiometer arrives with manufacturer pre-calibrated and ready to be used. It is capable of measuring radiance from 325nm to 1075nm wavelengths with a sampling interval of 1.6nm of the spectrum. The field of view of the instrument is about 25º. The reflectance of light on the canopy is collected by an optic sensor and data is sent to a portable PC via a RS232 to USB fiber link. Instantaneous graphs are displayed. To decrease the signal to noise ratio and increase the overall accuracy, integration time needs to be changed as light conditions change, while the dark current scan is automatically taken when every reflectance scan is taken. In addition, before taking the reflectance data, it should be calibrated by taking a white reference from a white reference panel.

Figure 5. FieldSpec radiometer was used to measure crop conditions

FieldSpec has a feature that allows the user to take sequential measurements. Users are able to specify “starting spectrum number”, “number of files to save” and “interval between saves” in the “spectrum save” dialogue box. The number of spectrum will be increased by one automatically every time a spectrum is saved (i.e. spectrum.001, spectrum 002, etc.). Spectral measurement data are stored in a unique file format that is only recognized by FieldSpec’s post-processing program, Viewspec. Therefore, data files must be converted into ASCII format using Viewspec, and then be viewed and analyzed in Excel. This instrument can be operated and data stored in three different modes: reflectance, radiance, or raw DN (digital number).

Multisensor Data Fusion Techniques

In the development of aerial precision sprayer for site specific pest management much research has been done with ground-based sprayers to reduce pesticide use and production costs, and to protect the environment. Technologies for aerial applications are becoming more available. One new approach for aerial application is variable rate technology (VRT), which consists of several precision agricultural technologies for applying a desired rate of crop production materials at a specific location. There is very limited application for commercial VRT devices due to their high cost and operational difficulty. An economic and user-friendly system is needed that could process spatially- distributed information, and apply only the necessary amounts of pesticides to the infested area, and much more efficient and minimize environmental damage. A key step in the system development is to develop prescription maps for aerial application using a remote sensing system and GPS/GIS technology. This makes it possible to perform multisensor, multi-spectral, multitemporal and even multi-resolution data fusion utilizing GIS technique to produce high quality prescription maps. The data fusion will be based on new methods for the fusion of heterogeneous data: numerical or measurable (radiometric, multi-spectral, and spatial information) and symbolic (thematic, human interpretation and ground truth) data. The multisensor data fusion scheme needs to be fully integrated into the system through GIS.

RESULTS AND DISCUSSION

NDVI Sensor

A GreenSeeker 505 Handheld Optical Sensor was mounted on a John Deere 4710 sprayer with a 30 meter swath and used to map the field while the sprayer applied a broadcast rate of 94 l/ha of defoliant to the field.

Data from the handheld optical sensor (figure 6) were georeferenced and converted to NDVI (figure 7). This data was imported into Farm Works software and classified based on NDVI values. The data was then smoothed using the inverse distance subroutine and prescription maps were generated for each of the remote sensing methods. Good correlation was obtained between the aerially-acquired images and the GreenSeeker data. Additionally, soil maps (figure 8) of the field obtained with a VERIS system, showed high correlation to NDVI values (figure 9) for the field.

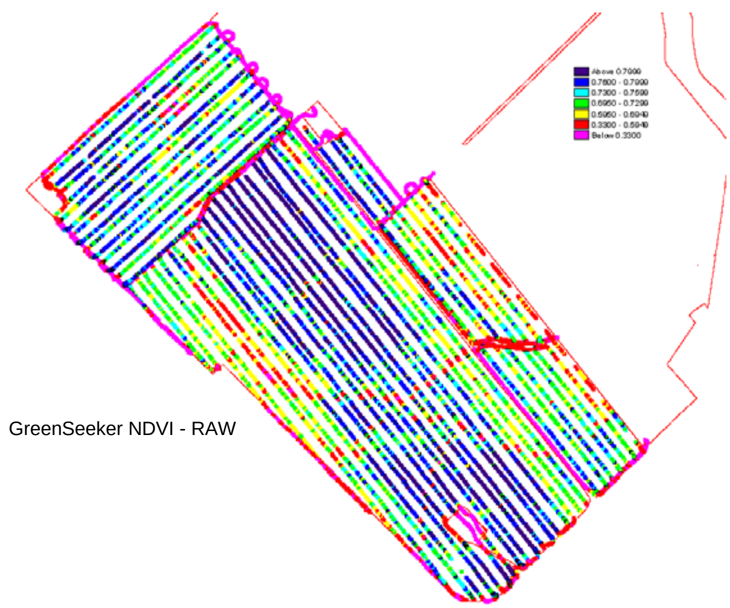


Figure 6. Raw GreenSeeker NDVI Data Grouped According to Data Range

Based on the results of this study, ground-based remote sensing with the GreenSeeker Handheld Optical Sensor is a viable alternative to more expensive aircraft-based remote sensing platforms.

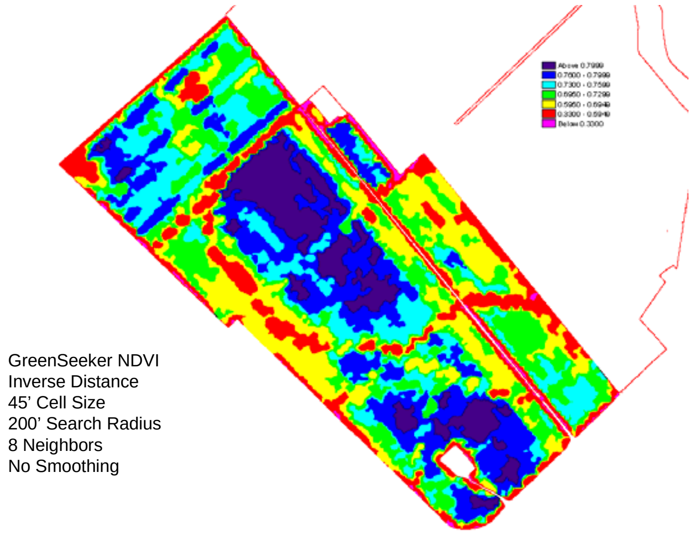


Figure 7. Processed GreenSeeker NDVI Data Grouped According to Data Range

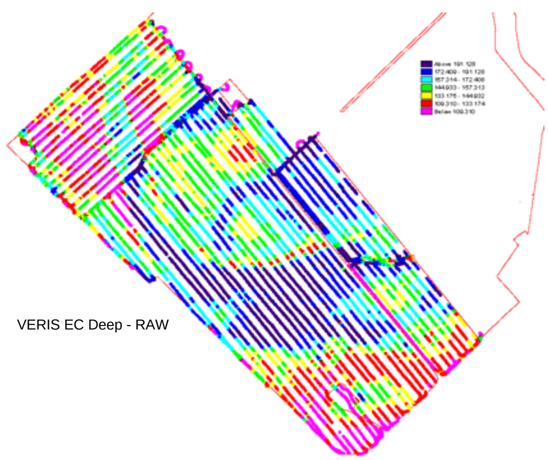


Figure 8. Raw Deep (0-36”) VERIS Soil Map Data Grouped According to Electrical Conductivity Data Range.

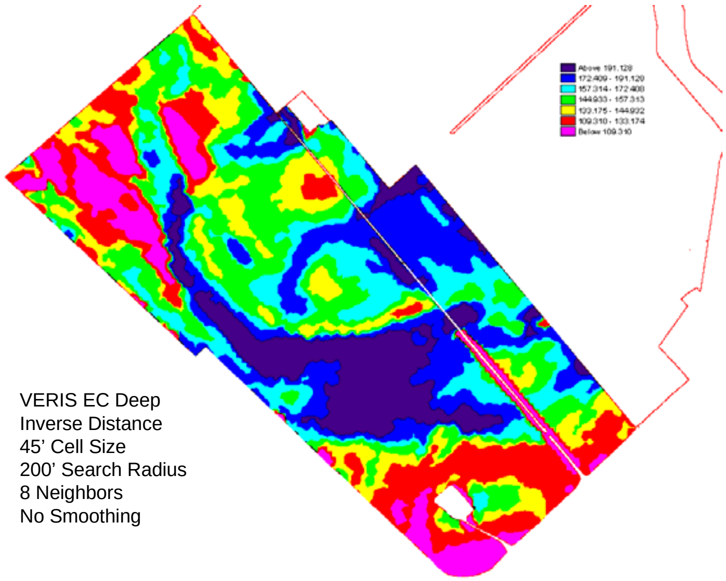


Figure 9. Processed Deep (0-36”) VERIS Soil Map Data Grouped According to Electrical Conductivity Data Range

Airborne Image Acquisition and Application

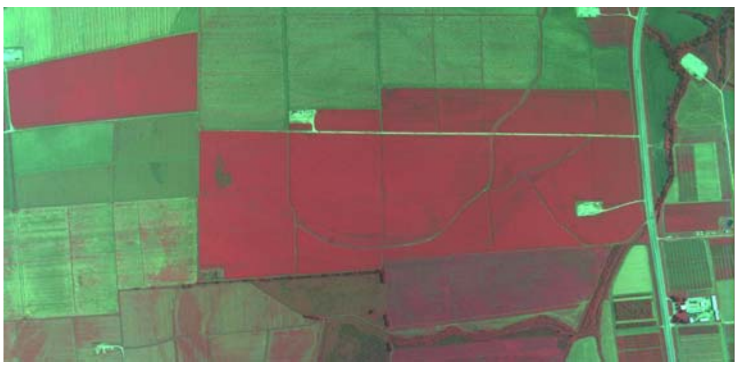
The hardware and software of the airborne multispectral imaging system were integrated, installed and configured on a single engine aircraft Cessna 206. The image correction software and ERDAS Imagine (Leica Geosystems Geospatial Imaging, Atlanta, GA), a remote sensing data processing software, were installed on a separate desktop computer for radiometric and geometric corrections respectively for the images acquired by the airborne multispectral imaging system. ERDAS Imagine was also used for further image processing to generate vegetation indices and to perform image classification and comparison. ArcGIS was installed on the desktop computer to provide the shape files of the fields and to interact with ERDAS Imagine to visualize the results of image processing. A GPS unit, MobileMapper CE (MMCE) (Thales Navigation, Inc., Santa Clara, CA), was used to record and map ground control points (GCP) in the fields to establish the spatial distribution of the ground truthing measurement.

The camera control system was operated on the Cessna 206 for imaging a number of fields for research of pest management starting March 2007. The purpose of the research was to determine the feasibility that the system is able to identify any pest issues in the fields concerned. For limited space the images of one field will be presented and explained.

This field is located in the eastern part of Burleson County in Texas. The field has a rotation of corn and cotton each year. This year cotton was planted. In September the field was ready for harvest. Before harvesting the field, defoliant was applied to facilitate the process of harvesting.

In order to implement schemes of site-specific application an overall map of the field was needed before defoliant application to provide a prescription for variable rate application. The use of the map was to reveal the spatial distribution of the cotton growth over the vegetated field and to identify the pest issues over the field for future farming.

Figure 10 shows the raw CIR DN image of the field on September 20 and the corresponding reflectance image of the field converted in the image correction software with the measurement of the irradiance radiometer on the same day. The reflectance image was brighten because the original reflectance image was too dark to visualize. Later the reflectance image was stretched with standard deviations to have a similar brightness and contrast with the DN image.



Raw CIR DN image

Brighten CIR reflectance image

Figure 10. Images on September 20, 2007.

The Cessna 206 carrying the integrated airborne multispectral imaging system flew over the field producing the image series over the two enclosed field polygons (figure 11). The first image in the series covers the field perfectly. It was chosen for further processing and analysis.

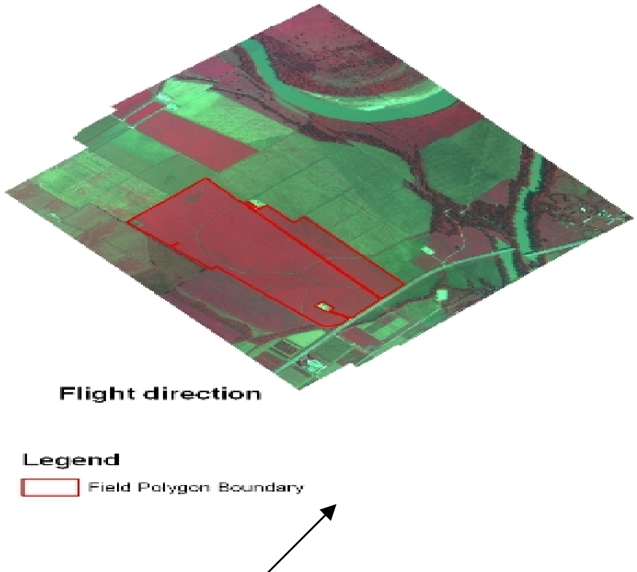


Figure 11. Image series on September 20, 2007.

As an important step of image processing geometric correction was conducted to reduce geometric distortion of the image and to perform georeference for the image. For geometric correction the GCPs were collected and used, and the image was resampled to match the WGS (World Geodetic System**)** 84 (Department of Defense, Washington, DC) with geographic location and orientation of the field (figure 12).

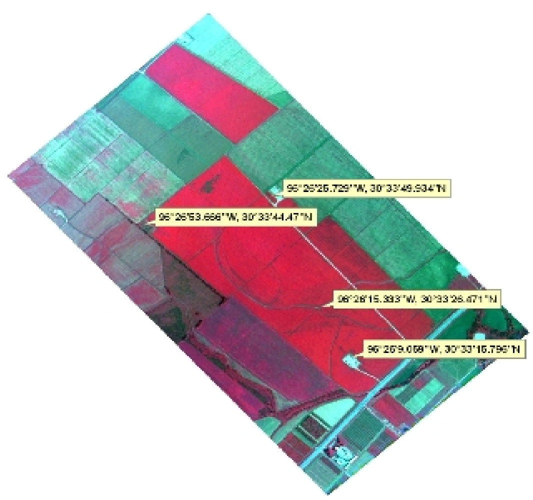


Figure 12. GCPs and geometrically corrected image on September 20, 2007.

After geometric correction the image should be cropped to the area of interest (AOI) to focus on the field concerned (Figure 13). By going over the image it was found that the field presented a pattern of center pivot irrigation, intersecting dirt roads, ditches, and varied vegetation of canopy mainly due to spatial change of soil profile over the field. The image also showed that two regions within the crop canopy in the field indicated different spectral signatures from the surrounding area. By field inspection it was discovered that a number of abandoned center pivot irrigation structures remained in Region A. Region B was infested with cotton root rot disease (figure 14).

Root rot is a typical pest issue in cotton growth. Identification of the region of cotton root rot and detection of the change of this pest issue are important for current and future farming of the field. For the purpose of identification and detection the image was further cropped into a much smaller CIR AOI to focus on the region of cotton root rot (figure 15). The image AOI was evaluated by individual bands and we found that the images of NIR and red bands indicated the existence of root rot region but the image in green band showed noise mostly without sufficient useful information (figure 15). In this way the NIR and red images and other images of certain combinations of the NIR and red images, such as NIR/red ratio and NDVI (Normalized Difference Vegetation Index), should be sufficient data sources to identify the region of root rot infestation.

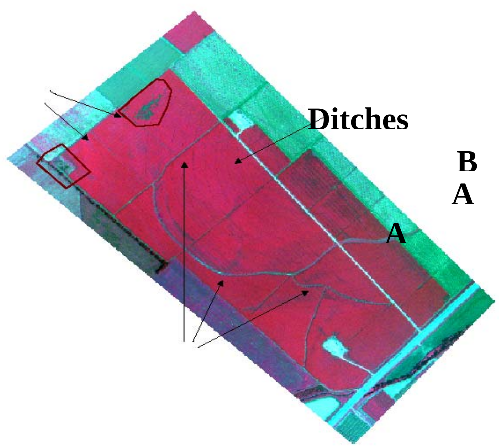
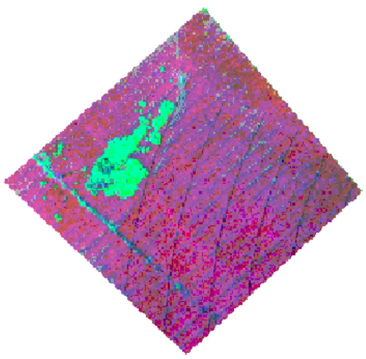


Figure 13. AOI of the processed image and features of the field demonstrated on the image on September 20, 2007.

Figure 14. Root rot of cotton crop.



CIR

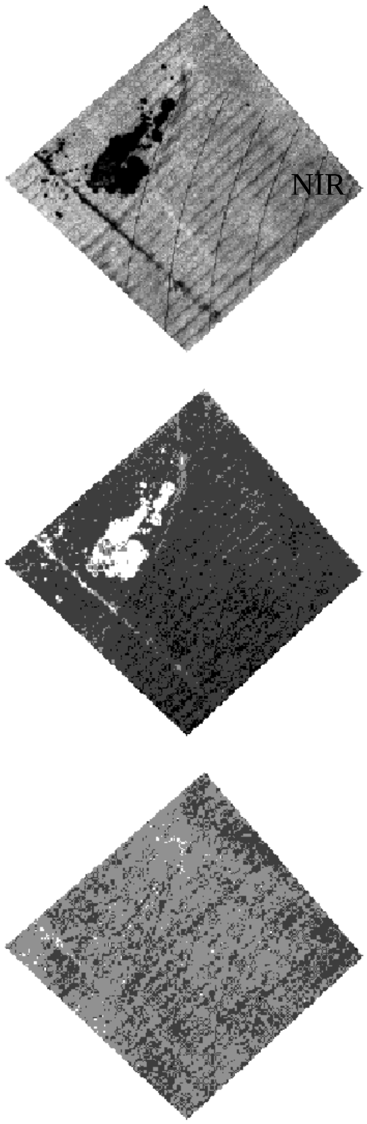
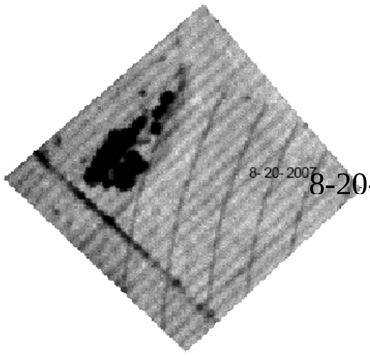


Figure 15. CIR AOI and individual band AOI images.

As shown above by spatial and spectral analysis of the image the root rot infested region could be identified. In order to detect the change of the root rot infested region the temporal analysis should be incorporated. Figure 16 shows the NIR images of the root rot infested region on August 20, September 14, September 20, September 27, October 2, October 5, and October 11 of 2007. The images on August 20, September 14, September 20, and September 27 showed the infested region clearly and on subsequent days the images still showed clearly even after the defoliant was applied on September 28, 2007. Therefore, all of the images were data sources to quantify the change of the root rot infestation in the region. However, care should be taken when examining the difference between images before and after defoliant application.



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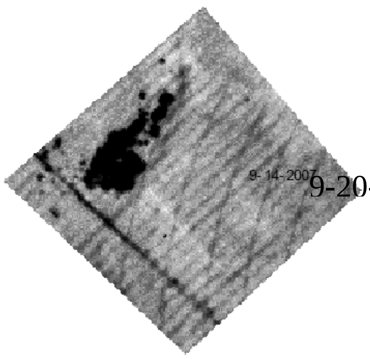
9-14-07



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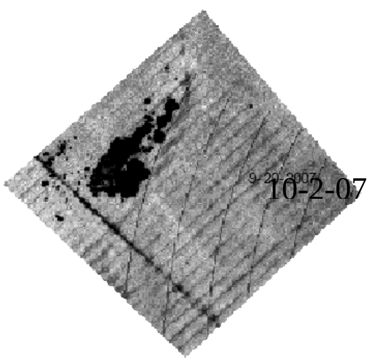
9-27-07



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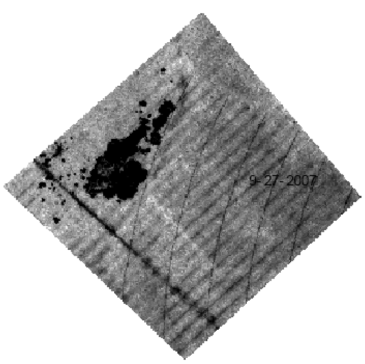

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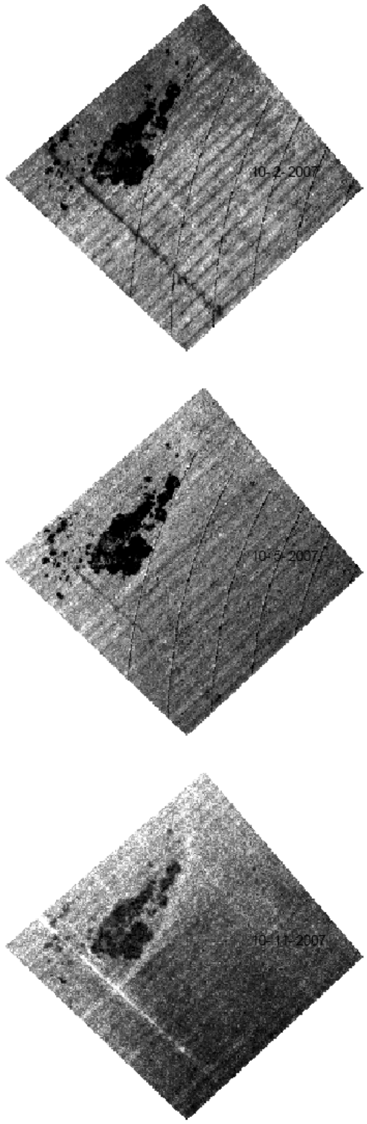

Figure 16. NIR images of the root rot infested region on different dates.

For variable rate application of defoliant over the field a prescription map is needed. To produce the prescription map the data revealing the spatially varied distribution of the cotton canopy is required. A number of options are available to provide the data. NDVI map is one option. Figure 17 is the NDVI map of the field, in which the bright pixels represent the strong vegetation points and the dark pixels represent fewer vegetation points.

Figure 17. NDVI image of the field on September 20, 2007.

CONCLUSIONS

The integration MS4100 multispectral camera with a specifically designed camera control system described in this paper has a great potential to be a cost-effective tool of airborne remote sensing in pest management. The automated multispectral imaging system is able to consistently produce images at or near vertical nadir view for the spatial, spectral and temporal analysis of pest issues. Through image processing the data from the system is able to convert into as the input for the prescription of variable rate application in site-specific pest management.

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REFERENCES

Cook, C.G., D.E. Escobar, J.H. Everitt, I. Cavazos, A.F. Robinson, and M.R. Davis. 1999. Utilizing airborne video imagery in kenaf management and production. *Industrial Crops and Products.* 9: 205–210.

Everitt, J.H., D.E. Escobar, R. Villarreal, J.R. Noriega, and M.R. Davis. 1991. Airborne video systems for agricultural assessment. *Remote Sensing of Environment.* 35(2–3): 231–242, color plate p. 230.

Everitt, J.H., D.E. Escobar, K.R. Summy, and M.R. Davis, 1994. Using airborne video, global positioning system, and geographical information-system technologies for detecting and mapping citrus blackfly infestations. *Southwestern Entomologist.* 19(2): 129–138.

Everitt, J.H., D.E. Escobar, K.R. Summy, M.A. Alaniz, and M.R. Davis. 1996. Using spatial information technologies for detecting and mapping whitefly and harvester ant infestations in south Texas. *Southwestern Entomologist.* 21(4): 421–432.

Hart, W.G., and V. I. Myers. 1968. Infrared aerial color photography for detection of populations of brown soft scale in citrus groves. *Journal of Economic Entomology*. 61(3): 617–624.

Hart, W.G., S.J. Ingle, M.R. Davis, and C. Mangum. 1973. Aerial photography with infrared color film as a method of surveying for citrus blackfly. *Journal of Economic Entomology.* 66(1): 190–194.

Heald, C.M., W.J. Thames, and C.L. Wiegand. 1972. Detection of *Rotylenchulus reniformis* infestations by aerial infrared photography. *Journal of Nematology*. 4:299–300.

Henneberry, T.J., W.G. Hart, L.A. Bariola, D.L. Kittock, H.F. Arle, M.R. Davis, and S.J. Ingle. 1979. Parameters of cotton cultivation from infrared aerial photography. *Photogrammetric Engineering & Remote Sensing.* 45(8): 1129–1133.

Hickman, M.V., J.H. Everitt, D.E. Escobar, and A.J. Richardson. 1991. Aerial-photography and videography for detecting and mapping Dicamba injury patterns. *Weed Technology*. 5(4): 700–706.

Medlin, C.R., D.R. Shaw, P.D. Gerard, and F.E. LaMastus. 2000. Using remote sensing to detect weed infestation in Glycine max. *Weed Science.* 48: 393-398.

Pinter, P.J., Jr. J.L. Hatfield, J. S. Schepers, E.M. Barnes, M.S. Moran, C.S.T. Daughtry, and D. R. Upchurch. 2003. Remote sensing for crop management. *Photogrammetric Engineering & Remote Sensing.* 69(6): 647-664.

Richardson, A.J., R.M. Menges, and P.R. Nixon. 1985. Distinguishing weed from crop plants using video remote-sensing. *Photogrammetric Engineering & Remote Sensing.* 51(11): 1785-1790.

Schneider, C.L., and G.R. Safir. 1975. Infrared aerial photography estimation of yield potential in sugarbeets exposed to blackroot disease. *Plant Disease Reporter*. 59(8): 627–631.

Yang, C., C.J. Fernandez and J.H. Everitt. 2005. Mapping phymatotrichum rot of cotton using airborne three-band digital imagery. Transactions of the ASABE 48(4):1619-1629.

Ye, X., K. Sakai, S. Asada, and A. Sasao. 2007. Use of airborne multispectral imagery to discriminate and map weed infestations in a citrus orchard. *Weed Biology and Management.* 7: 23-30.