RESPONSE AND POSITIONING ACCURACY OF A VARIABLE-RATE AERIAL APPLICATION SYSTEM AND USE OF ENHANCED IMAGERY FOR CREATION OF PRESCRIPTION MAPS

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ABSTRACT

Agricultural aircraft have been used at the USDA, ARS, CPSRU, Stoneville, MS USA for constant- and variable-rate application of crop protection agents and harvesting aids as well as remote sensing to support targeted application. The remote sensing systems have been designed to accommodate our research programs with a longer term goal of providing low-cost and accessible systems for agricultural pilots. This paper summarizes progress to date in evaluation of our variable-rate system for application accuracy and response, describes remote sensing systems to support our research programs and provide solutions for agricultural pilots, and describes concepts for image analysis systems that could be one solution for a turn-key system to support site specific crop management from agricultural aircraft.

Keywords: Aerial Application, Remote Sensing, Thermal Imaging, Variable-Rate Application, Vegetation Indices

INTRODUCTION

Agricultural aircraft are primarily used to apply chemical and biological crop protection agents, harvesting aids, and nutrients to promote a high-yielding and economically viable crop. One focus of research at the USDA, ARS, CPSRU in Stoneville, MS USA has been on evaluation of a variable-rate (VR) aerial application system for its ability to change rates quickly and to place material at the correct field location. The latter is especially important when spray needs to be halted close to field buffers based on a GPS-programmed spray plan. Use of the agricultural aircraft platform has been further expanded to implement several types of remote sensing cameras for research, with a longer range goal of providing the aerial applicator a tool to image fields.

Only recently have agricultural aircraft been equipped to implement variable-rate application to match site-specific needs of the crop. ‘Variable-rate’ application implies that several rates can be applied (and are useful) for farm management from an aerial platform. Although a variable-rate aerial application system may have the engineered capability to apply several programmed rates, practicality for field management has usually been limited to zero flow, maximum flow, and maybe one intermediate flow for applications that depend upon variable crop vigor. Crop vigor can be quantified by vegetation indices developed via remote sensing imagery. Robinson (2005) reported on early field use of aerial variable-rate technology, where a 49.2 percent savings in plant growth regulator (PGR) application was indicated versus blanket application on a 126 ha field. Application of insecticide is sometimes done via tank mix with PGR. The problem with application of insecticide via tank mix is that, in order to avoid applying a sub-lethal dose, insecticide may be overexpended to put out the higher rates of PGR. An injection system that allows metered amounts of chemical in separate tanks could help alleviate that problem, and new systems that meter dual rates are now available (Hemisphere, 2012). The DIVRA system (Pay's Air Service, 2012) is in wide use in Australia. This system directly injects chemical into a mixture that maintains essentially constant volume, thereby assuring optimal droplet size for maximum efficacy and drift reduction.

Several remote sensing systems are being used on the agricultural aircraft platform at the CPSRU. These systems include digital video, thermal, multispectral, and hyperspectral systems. Imaging platforms are being used for detection of crop injury due to drift of herbicide (Ortiz et al., 2011; Reddy et al., 2010; Huang et al., 2010) and crop heat/water stress as influenced by water deficit (Thomson and Sullivan, 2006; Thomson et al., 2012). Digital video (Thomson et al., 2005), compact three and six-band multispectral systems, and a thermal imaging system (Thomson et al., 2012) have potential for use by aerial applicators to implement practical on-farm management. A fully integrated system incorporating remote sensing, rapid image processing with image georegistration, and variable-rate application would be of great benefit to aerial applicators, but it is essential that image interpretation be done accurately with involvement of the crop consultant to help select field areas to segment for variable-rate application.

Commercial agricultural services that simply supply remote sensing data and prescription maps for variable-rate application started strong with many ideas on what could be accomplished profitably. However, economic reality limited the scope of practical applications, although technologies for ground-based VR systems have advanced considerably. In-Time (2009) was incorporated in 2003 to provide steps for creation of field prescriptions that could be loaded directly into a ground sprayer or an airplane's guidance/flow control system. In-Time and services like it such as John Deere Agri-Services' OptiGro® Variable Rate Imaging System (Delta Farm Press, 2006) had relatively fast turnaround for image production, but total time to create a prescription map from images was variable. In-field scouting by crop consultants was necessary for final creation of prescription maps. In this case, carefully interpreted remote sensing imagery was used as the essential starting point. The OptiGro system is now an inclusive farm management system (Sanders, 2012) that incorporates precision soil sampling, variable rate fertilizer, field mapping, aerial imaging, yield data processing, and support for both ground and aerial variable-rate controllers.

This paper summarizes much of our progress to date in evaluation of variable-rate aerial application systems, aerial remote sensing systems, and rapid image processing for creation of prescription maps using the agricultural aircraft platform.

VARIABLE-RATE AERIAL APPLICATION

System Evaluations

Although there are minor variations, three major methods are available to control liquid flow for tank mix-based aerial variable-rate systems. An in-line ball valve to control flow to the boom is the most common method. It is a simple method of control but has issues with flow response to changing rates. Variable pitch spray pump propellers controlled manually or by a servo are also used, followed by hydraulically operated spraying systems. The latter responds fastest to changing rates but is also the most expensive. However when compared with the total outlay for the aircraft and guidance system, cost (about 5% of the total) is not prohibitive.

Our studies used a hydraulically operated variable–rate system consisting of a Satloc Airstar M3 guidance system (Hemisphere, Inc, Calgary, Canada), AutoCal flow controller (Houma Avionics, Houma, LA. USA), and Kawak Aviation hydraulic power pack (Kawak Aviation Technologies, Bend, OR. USA) on an Air Tractor 402B aircraft. In an experiment to evaluate positioning accuracy and response time to changing rates (Thomson et al., 2009), water sensitive paper (WSP) cards were placed perpendicular to the spray swath, and the aircraft was flown several times with a GPS receiver signal to activate the spray system at a specified field location. WSP showed that average spray deposition position error magnitude was 5.0 m when traveling east to west and was 5.2 m when traveling north to south. Flow controller error and variable rate system error were evaluated from data collected while making applications to a series of four management zones with several application rates. Variable rate system error due to rate change timing was evaluated by comparing applied rates from the system to required rates from the prescription. Area under time plots of for application rate showed that average rate timing error for six application passes ranged from -9.1 to 1.4 percent. System response was then re-evaluated as a result of algorithm improvements (Thomson et al., 2010). Results for south-north runs indicated reduction of average error from 6.9% before control algorithm modification to 1.8 % after algorithm modification.

REMOTE SENSING SYSTEMS AND APPLICATIONS

Digital Video

An instrumentation system for imaging studies has been developed for an Air Tractor 402-B airplane. A guide-rail supported box, designed to slide into the cargo bay of the airplane, houses all image acquisition devices.

Digital video systems have included the older Sony model DCR TRV-103 digital8 video camera, Sony GV-D800 DV VCR, Panasonic NV-GS120 DV, and Sony HDR-CX190 HD camcorder. The first two systems were interfacable with a VMS-200 video mapping system (Red Hen Systems, Fort Collins, CO., USA) that accepts input from GPS. While the video camera was operating, the VMS-200 received data from the GPS every second and recorded the data to the audio track of videotape. The cameras were operated using their IR remote controls from the cockpit with IR signal sent to the cameras via a fiber optic cable (Thomson et al., 2002). A 4-inch monitor allowed the pilot to see the ground via video pass-through, and a pilot signaling system was designed to indicate whether the camera was paused or recording (Thomson et al., 2007b). The DV VCR could also be operated remotely, and it could accept input from any camera with NTSC output such as a Raytheon Palm-IR Pro thermal imaging camera (Thomson and Vogt, 2003).

Digital video was useful for detection of weeds and toxin-producing algae in catfish ponds (Thomson et al., 2005). For the weed experiment, weeds were intentionally allowed to proliferate in a small field of early cotton. A mixture of spotted spurge (*Euphorbia maculata* L.) and hyssop spurge (*Euphorbia hyssopifolia* L.) were distinguishable from both early cotton (*Gossypium hirsutum* L.) and Johnsongrass (*Sorghum halepense* (L.) Pers.) using the Mahalanobis Distance supervised classification (a scale-invariant classification method). The raw RGB image indicated cotton, spurge, and johnsongrass correctly classified with 73%, 67%, and 82% accuracy, respectively. For detection of toxin-producing algae, an inverse relationship between chlorophyll a (chl-a) and raw digital numbers was indicated (R=0.56). To account for varying illumination in detection of weeds, bands can be combined and registered using multiple cameras. Gumz and Weller (2006) used waveband combinations (Spectral Vegetation Indices or SVI) to distinguish weeds such as Velvetleaf (*Abutilon theophrasti* Medik), Lambsquarters (*Chenopodium album* L.), and Powell's Amaranth (*Amaranthus powellii* S. Watson) from various types of Mint. Good discrimination was observed using simple narrow-band wavelength ratios.

Thermal Imaging

Thermal imaging can illustrate spatial differences in canopy temperature, but temporal differences are more difficult to quantify since differences in weather and acquisition height influence temperature registered at the camera. A study was therefore conducted to develop relationships between altitude/weather variables and canopy temperature (Thomson et al., 2012), with the eventual aim of using canopy temperature data to assist with irrigation scheduling. An Electrophysics PV-320T thermal imaging camera (Sofradir EC, Inc., Fairfield, NJ, USA) of 320 X 240 pixel resolution was used in the agricultural aircraft to obtain thermal imagery in the 7 -14 μm spectral range. To quantify altitude effects on temperature represented at the camera, the pilot was instructed to spiral up and then back down to obtain several images over an area of a soybean field of high temperature uniformity. Uniformity was essential because a pixel represents different ground areas at different heights. Multiple Regression Analysis indicated that altitude explained 58% of the variability in canopy temperature and was statistically significant at the 0.01 level. With additional variables introduced, [Altitude + Photosynthetically Active Radiation (PAR)] accounted for 73% of the variability in canopy temperature and [RH + altitude] accounted for 76 % of the variability in canopy temperature.

Multispectral Imaging

Tetracam 6-band MCA

The Tetracam MCA (Multiple Camera Array) Series camera (Tetracam Inc., Chatsworth, CA, USA) consists of six sensor channels of 10 bit SXGA (1.3 megapixel) data, an image large enough to capture 130 hectares at 1 meter resolution. Each channel has a detector/bandpass filter/lens mounted in a common, factory aligned optical block. The filter passbands are designated at time of order and field-replaceable using standard 25mm spectrometer filters. The system can be connected to an external GPS receiver outputting NMEA sentences, and camera coordinates at time of image capture associated with image data are later recovered. This multispectral camera is being evaluated as a likely candidate for practical on-farm remote sensing from agricultural aircraft.

Geospatial Systems MS4100

The MS 4100 camera (Geospatial Systems, Inc., West Henrietta, New York USA) is a multi-spectral 3-CCD (Charge-Coupled Device) color/CIR (Color Infrared) digital camera with 1920 (horizontal) ×1080 (vertical) per-sensor resolution. The camera images the four spectral bands from 400 to 1000 nm, and acquires separate red (660−40 nm bandwidth), green (540 − 40 nm bandwidth), blue (460 − 45 nm bandwidth), and NIR (800−65 nm bandwidth) image planes. The red, green, and NIR bands approximate Landsat satellite thematic mapper bands (NASA, Washington, D.C.; USGS, Reston, Va. USA). This system was used successfully to detect crop injury caused by drift of glyphosate (Huang et al., 2010). Processed Rubidium Chloride (RbCl) tracer data from ground sampling stations and image data were highly correlated, with correlation coefficients (r) ranging from -0.60 one week after treatment (WAT) to -0.93 three WAT. Results indicated that spray drift sampling could explain early cotton injury 1 WAT, and airborne remote sensing could explain injury to cotton 2 WAT.

Hyperspectral Imaging System

The Pika II (Resonon, Bozeman, MT USA) is a line-scan hyperspectral imager that creates a streaming image of pixel-by-pixel spectral data with a spectral range of 400 to 900 nm. The system has been adapted to the agricultural aircraft, and system evaluation is underway. Plant injury studies conducted in both greenhouse and field at the CPSRU will be assisted by specification of narrow-band wavelengths most sensitive to differences in crop injury. This will allow earlier detection of crop injury due to off-target pesticide drift and low dose application. For practical use, narrow-band filters will be selected around the most sensitive bands indicated by hyperspectral analysis for implementation in a multispectral imaging system such as the aforementioned Tetracam 6-band MCA.

RAPID ACQUISITION AND PROCESSING OF IMAGERY FOR DEVELOPMENT OF PRESCRIPTION MAPS

Use of agricultural aircraft as a platform for both remote sensing and spraying has obvious advantages in convenience for research. A necessary component for integrating remote sensing imagery with variable-rate aerial application for the applicator is a system for rapid image processing. It is not realistic or even desirable to spray from an aerial platform simultaneously with image acquisition as can be done with some real-time ground application or "spot-spraying" systems (Hanks and Beck, 1998; Trimble, 2012). However, with a properly programmed system, images could be acquired on one pass, quickly analyzed to create a prescription, and the prescription could then be applied on a subsequent spray pass.

One system with potential for near real-time processing has been documented by Thomson et al. (2007a) that automatically georegistered imagery and transferred data to a site specific farming program. Electronics were developed to perform all control functions for the camera system. This system utilized a vigor-based index (Normalized Difference Vegetation Index or NDVI) much like the In-Time (2009) system but could also be used for any vegetation index appropriate for the field variable of interest. Color-infrared images were processed into the system and automatically georeferenced using both an on-board GPS and plane attitude sensor. A single board computer controlled image acquisition and acquisition of data from the sensors, which were passed to the flight computer through the Microsoft Windows Hyperterminal data communications program. The software determined the correct time between photos, and produced a percent overlap in the images. Conversion software used standard trigonometry and plane attitude data to determine a center coordinate in the image (assuming a flat field). The program then stepped across the image to determine an average NDVI value and GPS coordinate for each box. The process was repeated until the entire image was transformed. Georeferencing accuracy was a limitation of an early version of this system, as average Root Mean Square (RMS) error for all images was 56 meters. This value was not acceptable for prescription map generation and was no better than initial experiments on video-based image georeferencing with one-second GPS updating (Thomson et al. 2002). Improvements that accounted for consistent positioning errors and time synchronization improved this error to less than to 10-m.

DISCUSSION

As technologies have improved, our experiences with remote sensing and variable-rate aerial application from the agricultural aircraft platform have indicated the following needs for practical adoption:

1. Response and accuracy of variable –rate aerial application systems have thus far been evaluated for hydraulically actuated flow controllers. Although these have a successful market, the predominant systems still utilize ball valves and spray pumps that use variable-pitch propellers. These systems respond more slowly to changing rates, but a control scheme that uses these two systems synergistically might increase their acceptability for variable-rate aerial application. Fast response is especially important where it is critical to turn a system off at the correct field location near spray buffer zones.

2. Multiband imaging cameras now available for practical use on agricultural aircraft have the convenience of changing optical filters easily. A six band imaging system can most likely detect field variables needed for variable-rate application from agricultural aircraft. These optical filters are selected based on the specific field variable observed (e.g. plant vigor differences, crop injury, nutrient stress) by using hyperspectral imagery and ground-based spectroradiometry, which determine wavebands most sensitive to spatial or temporal changes in the field variable.

3. A rapid image analysis scheme could allow interpreted remote sensing data to be used in developing management zones for variable-rate aerial application. However for practical scheduling, field scouting and involvement by the crop consultant are still desirable to ultimately delineate zones for segmentation and variable application.

4. Variable-rate aerial application (e.g. of harvesting aids) using vigor-based vegetation indices derived from imagery have seen the most success in real-world settings. Further research to better quantify nutrient status for variable-rate dry or liquid application from aircraft and systems that use dual tanks and chemical injection have the potential for expanding use and acceptability of aerial variable-rate technologies.

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