

DEVELOPMENT OF UNMANNED AERIAL VEHICLES FOR SITE-SPECIFIC CROP PRODUCTION MANAGEMENT

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ABSTRACT

Unmanned Aerial Vehicles (UAV) have been developed and applied to support the practice of precision agriculture. Compared to piloted aircrafts, an Unmanned Aerial Vehicle can focus on much smaller crop fields with much lower flight altitude than regular airplanes to perform site-specific management with high precision. In crop production management, UAVs have been developed and used for chemical application and remote sensing. Agricultural application of fertilizers and chemicals is frequently needed at specific time and location for highly accurate site-specific management. Routine monitoring of crop plant health is often required with super-resolution for highly accurate site-specific management as well. UAVs are the technology to fulfill the goals of such crop management. This research overviews the development of UAVs for crop production management. The development of an ultra low volume sprayer for a UAV helicopter is described. The results of the field study are analyzed and discussed. Two other UAVs, one helicopter and one fix-wing airplane, are evaluated for low-altitude remote sensing over crop fields. The integration of the spray technology and the remote sensing technology on the UAV systems provides a great potential to identify crop stresses and hence spray crop production and protection materials at different rates over small crop fields to realize highly accurate site-specific crop production management.

Keywords. Unmanned aerial vehicle, crop production management, chemical spray, remote sensing

INTRODUCTION¹

An unmanned aerial vehicle (UAV) is an unpiloted, autonomous unmanned aircraft that can be remotely controlled or fly autonomously based on pre-programmed flight plans or more complex dynamic automation systems. UAVs have been developed to support precision agriculture. Piloted aircraft that carry a sprayer and/or an aerial imaging system can cover well over hundreds of hectares of crop fields. However, piloted aircraft are not prevalent in all areas, so remote sensing alternatives are needed. Field operations over smaller fields can especially benefit from use of UAVs.

This paper presents an overview of UAV development for crop production management. Development of an Ultra Low Volume (ULV) sprayer for a UAV helicopter is described. The results of the field study are analyzed and discussed. Two other UAVs, one helicopter and one fix-wing airplane, are presented as options for remote sensing over crop fields.

OVERVIEW

The Yamaha Motor Corporation (Iwata, Shizuoka, Japan) produces the most advanced non-military UAV. Primarily the Yamaha UAV is developed and used for agriculture application, like insect pest control of rice paddies, soybeans and wheat. The first system, RCASS, was built in 1980. Later on, in 1990, the helicopter R50 had a payload of 20 kg and a laser-system for height determination. In 1997, the type RMAX came out and 3 years later it was equipped with an azimuth and differential Global Positioning System (GPS) sensor system (Yamaha, 2004). Miller (2005) reported an experiment to determine the effectiveness of using an UAV for dispersing pesticides to reduce human disease due to insects. In this experiment a commercial off-the-shelf Yamaha UAV, the RMAX type, was outfitted with both liquid and granular pesticide dispersal devices, and a series of tests were performed to evaluate the effectiveness of the UAV to perform aerial pesticide delivery.

SR series UAV helicopters have been developed recent years by Rotomotion, LLC (Charleston, SC). These helicopters are fully autonomous, unmanned vertical take-off and landing UAVs. Huang et al. (2009) developed a low volume spray system for use on a SR200 UAV helicopter. In this project a spray system was developed and integrated with the flight control system of SR200 which has a maximum payload of 22.7 kg. The integrated sprayer was developed to be triggered by preset positional coordinates received from the GPS system of the UAV through a PWM (Pulse Width Modulation) pump speed controller. This spray system has been evaluated in the lab. Our research in this paper further evaluated the system for low volume spray in a small scale field, which will promote the application of the system for crop production management.

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.

UAV-based agricultural remote sensing systems have been described in numerous previous reports. Johnson et al. (2001) developed remote sensing technique on UAV for vineyard management. Fukagawa et al. (2003) developed a Radio Controlled (RC) helicopter based crop growth monitor system using a multispectral image sensor. Jensen et al. (2003) used digital imagery acquired from a UAV for assessing grain crop attributes. Simpson et al. (2003) developed a low-cost RC UAV platform for agricultural remote sensing. The developed UAV carried imaging sensors over a target area. The system successfully captured aerial images of several locations. Herwitz et al. (2004) used NASA (National Aeronautics and Space Administration)'s solar-powered Pathfinder-Plus unmanned aerial vehicle (UAV) to conduct a proof-of-concept mission in US national airspace above the 1500 ha plantation of the Kauai Coffee Company in Hawaii. Sugiura et al. (2004) used an unmanned helicopter to introduce a three-dimension Geographic Information System (GIS) map generation system by integration of UAV image data and topographical data. Hardin and Jackson (2005) developed an UAV system rangeland photography. Hunt et al. (2005) developed a high-resolution multispectral digital photography system using UAV. Macaithur et al. (2005) proposed a remotely piloted mini helicopter imaging system for determining citrus tree health and characteristics. Sugiura et al. (2005) developed a system that can generate a map regarding crop status obtained by mounting an imaging sensor on an unmanned helicopter. Sullivan et al. (2007) evaluatee a less expensive system, an UAV equipped with a thermal infrared sensor, for detecting cotton response to irrigation and crop residue management. Swain et al. (2010) used a RC unmanned helicopter-based Low-Altitude Remote Sensing (LARS) to acquire quality multispectral images of high spatial and temporal resolution, in order to estimate yield and total biomass of a rice crop.

Xiang and Tian (2006, 2007a and 2007b) developed a multispectral imaging platform using Tetracam ADC camera (Tetracam Inc., Chatsworth, California) on the Rotomotion SR100 UAV helicopter. They have evaluated the integrated system of the multispectral imager and the flight control system of the UAV helicopter, which has proven improvements of the spatial and temporal resolutions and the reliability over the conventional remote sensing platforms. Huang et al. (2008) studied the Rotomotion electric SR20 UAV helicopter for LARS. The Tetracam ADC camera was mounted and developed to be triggered by preset positional coordinates received from the GPS system of the UAV. It is our goal to fully develop this UAV or other inexpensive UAV to carry a low-cost, light-weight multispectral camera to acquire imagery for crop production management. This paper presents our further efforts for this goal.

UAV SYSTEMS

Aerial Sprayer

System Design and Development

Rotomotion's SR200 was selected as the platform for integrating a ULV sprayer. The SR200 is a Vertical Take-Off and Landing (VTOL) unmanned autonomous helicopter powered by a two stroke gasoline engine. It has a main rotor diameter of 3 m and a maximum payload of 22.7 kg. After subtracting for the 2.25 kg standard undercarriage, the net useable payload is 20.25 kg . If a 0.45 kg

generator, a 0.45 kg high-performance telemetry, and a gallon of gas with tank (3.15 kg) are deducted, 15.75 kg payload is left for mechanical and electronic components of the sprayer. These components include spray pump, pump speed controller, chemical with tank, tubing, and nozzles.

The sprayer on the UAV is required to spray at a low volume with a spray rate of 0.3 L/ha to cover at least 14 ha. If the specific gravity of the chemical is 3.3 kg/gal, about 1.5 gallon chemical is needed to cover the 14 ha land. If the spray swath width is 30 meters swath and the air speed of 2.2 m/s (5 mph), the pumping rate of the sprayer needs about 100 mL/min. The SR200 uses one gallon of gas for every 45 minutes.

A ULV sprayer was designed and constructed to be easily mounted onto the SR200. The sprayer directly interfaced with UAV's electronic control systems to trigger spray release based on specified GPS coordinates and preprogrammed spray locations. The sprayer mainly includes four components; a boom arm with mounted spray nozzles; a tank to house the spray material; a liquid gear pump; and a mechanism to control spray activation. All of these components, along with chemical, must weigh less than 15.75 kg as discussed above for SR200.

Micronair ULV-A+ rotary nozzles (Micron Sprayers Ltd, Bromyard, Herefordshire, UK) were selected for the sprayer (Huang et al., 2009). A one-and-half-gallon spray tank was designed and built with two internal baffle plates to minimize sloshing of the spray material load during flight (Huang et al., 2009). The tank weighs 1 kg plus 5 kg for one and half gallon chemical, which results in the 9.75 kg net payload of the UAV.

Aluminum tubing with all-plastic Micronair nozzles, gear pump, and control box restrict the weight of the rest of components of the sprayer to less than 9.75 kg.

Fig. 1 shows the ULV sprayer integrated with the SR200 UAV helicopter.



Fig. 1. SR200 UAV helicopter spray system with spray system mounted on the undercarriage.

The ULV sprayer for the UAV was evaluated by spraying BVA oil, a crop oil used to mimic real-world tank solutions, thereby, limiting the use of active

ingredients in nozzle test (Huang et al., 2009). The evaluation was conducted using the measured flow rates to determine the needed number of nozzles needed on the spray system for the 30 meter swath width, air speed of 2.2 m/s, and a spray rate of 0.3 L/ha. The results indicate that for vector control (< 50 μm droplet size) with the targeted spray rate, 2, 3 and 4 Micronair ULV–A+ rotary nozzles are needed, depending on the applied pump voltage (Huang et al., 2009).

Field Test

A field test was conducted to determine the sprayed deposition for a 30 meter swath width of the ULV sprayer for the SR200 UAV. Three Micronair ULV A+ rotary nozzles were used for the test on the boom. The nozzles were calibrated to deliver 100 mL/min. The sprayer released the liquid at the heights of 3.7m and 6.1 m driven at 4 V and 6 V DC (Direct Current) power for less than 50 μm droplet size. The moving speed of the spray structure was at 2.2 m/s. The spray solution was the mixture of the BVA 13 ULV Oil® (Adapco, Inc., Sanford, FL), which has very similar physical properties to the oil-based insecticide Anvil 10+10® (Clarke Mosquito Control, Roselle, Illinois) and Uvitex at 1.25 g/L for spectrofluorometer readings related to spray deposition.

Two spray measuring devices were used: monofilament lines and spinners. The monofilament lines were used to capture airborne sprayed materials at distances from 0-42m downwind of the spray line. The spinners were used to capture fine droplets floating in the air in the swath downwind. Fig. 2 shows the layout the test field. In the field monofilament lines were placed at 0, 6, 12, 18, 24, 30, 36 and 42 m downwind from spray structure moving line, 30 m sections of monofilament lines were held at 1 m above the ground. The lines were collected using the specially constructed holders and the cordless drills. The spray lines were placed in a labeled holder. The spinners were installed at 6, 18, 30, and 42 m downwind from spray structure moving line on the top of one monofilament line station on the east side at the distance. Each spinner was mounted a pair of 7.6 cm glass bars to capture fine droplets floating in the air.

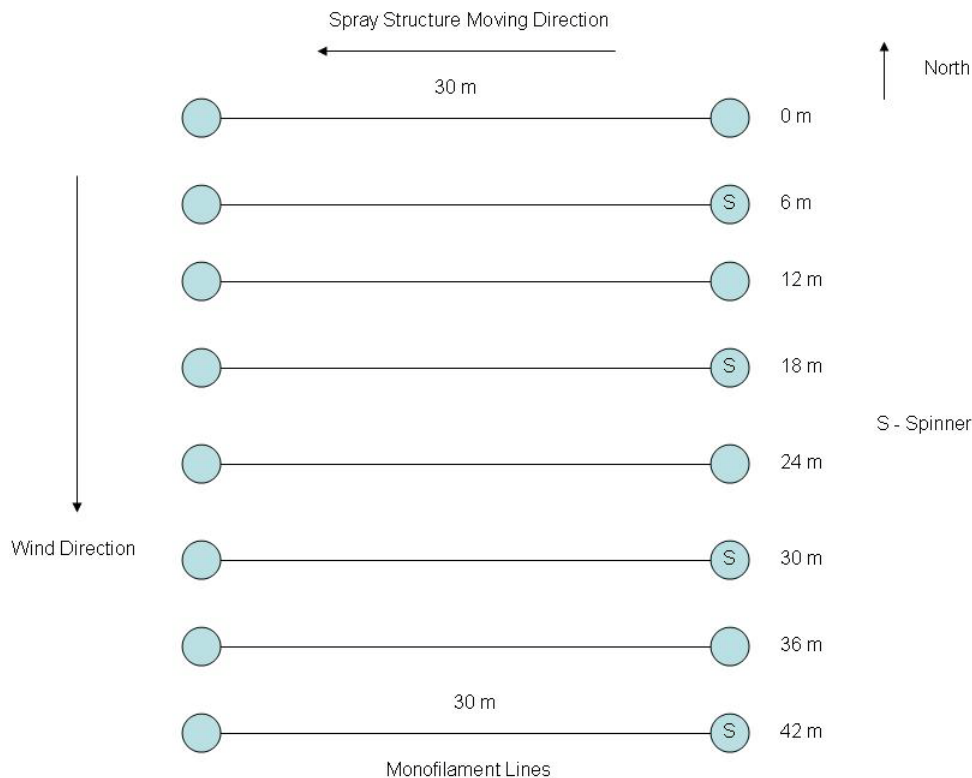


Fig. 2. Field layout of the ULV sprayer test.

Eight passes were run for the test with 2 DC power voltages x 2 release heights x 2 reps. Sixty four PVC (Polyvinyl chloride) tube holders were used to hold the spray lines with 8 passes x 8 lines. Thirty two labeled polyethylene bags were used to hold 32 pairs of glass bars from spinners with 8 passes x 4 stations.

Sample processing was conducted by pipetting 10 and 30 ml of 100% hexane wash into each polyethylene bag and each PVC line holder, respectively, agitating the sample bag and holder (approx. 15 sec for glass bars and 30 sec for monofilament lines), and decanting 6 ml into a cuvette. The dye concentration ($\mu\text{g/ml}$) of samples and tank mixture were measured using a spectrofluorometer (Shimadzu, Model RF5000U, Kyoto, Japan) with an excitation wavelength of 427 nm and an emission at 489 nm. The minimum detection level for the dye and sampling technique was 0.07 ng/ml. The sample concentration was multiplied by the wash volume and divided by the effective sample area to get μl of dye/ cm^2 .

Mylar plate and ear silks samples were washed in 30 mL of ethanol in the collection bags. Samples were agitated to allow time for dye to dissolve into solution in the ethanol. A sample portion of the wash effluent was placed in borosilicate glass culture tubes (12 x 75 mm). The cuvettes were then placed into a spectrofluorophotometer (Shimadzu, Model RF5000U, Kyoto, Japan) with an excitation wavelength of 427 nm and an emission at 489 nm. The fluorometric readings were converted to $\mu\text{L}/\text{cm}^2$ by comparisons to standards generated using the actual oil and dye mix used. The minimum detection level for the dye and sampling technique was 0.07 ng/ cm^2 .

Statistical analysis was conducted to profile the spray deposition downwind under different power voltages, release heights, and downwind distance. For the analysis the SAS GLM procedure was run using SAS for Windows software (version 9.1.3) (SAS Institute Inc., Cary, NC, USA).

Aerial Imager

SR20-Based System

Rotomotion provides another UAV helicopter, SR20. SR20 utilizes the same control and communication systems as SR200. Compared to SR200 SR20 is a much smaller UAV. SR20 is an electric VTOL UAV with a main rotor diameter of 1.75 m and a maximum payload of 4.5 kg. SR20 carries a light weight video camera to produce real-time aerial imagery being sent back to the ground control station. The mount of the video camera can be modified to hold a light weight multispectral camera.

The Tetracam ADC camera is selected as the multispectral camera on the UAV. The camera weighs 640 grams with 8 AA alkaline batteries. It is equipped with a 3.2 megapixel CMOS (Complementary Metal–Oxide–Semiconductor) sensor (2048 x 1536 pixels) or a 5.0 megapixel CMOS sensor (2560 x 1920). The camera has green (520 – 600 nm), red (630 – 690 nm) and NIR (Near InfraRed, 760 – 900 nm) sensitivity in the bands approximately equal to Landsat Thematic Mapper 2, Thematic Mapper 3 and Thematic Mapper 4 (NASA, Washington, DC). Band information provides data needed for extraction of NDVI (Normalized Difference Vegetation Index), SAVI (Soil Adjusted Vegetation Index), canopy segmentation, and NIR/Red and NIR/Green ratios. Standard GPS data capture from an external receiver adds position data to the images. The 3.2 megapixel ADC fitted with an 8.5mm lens is able to achieve a 0.5 meter/pixel ground resolution at 1340 m AGL (Above Ground Level).

Sig Kadet Senior-Based System

Sig Kadet Senior (Sig Manufacturing Company, Inc., Montezuma, IA) is a model airframe designed in 1980s (Fig. 3). The airframe has a length of 1,644.6 mm with 2,044 mm wing span and 76.1 dm² wing area. The UAV system was integrated from the airframe with other three systems: engine, avionics (RC servos and autopilot), and image sensor (camera).

The engine chosen to power this UAV is the *O.S. Engine Max 61 FX* series. The engine was chosen to increase the UAV power due to the increased payload or cargo associated with the avionics and camera systems. The engine is a glow plug, ring less, 2-stroke internal combustion engine that runs on glow fuel (methanol and/or nitromethane).

The avionics are the basic radio controls used in model aircraft (manual flight control) and the autopilot system (automated flight control). The RC system is employed during take-off, landing, and autopilot failure. The system consists of a radio transmitter (ground based), radio receiver (aircraft based), and electronic servos (convert radio signals into flight surface movement). The autopilot system is a digital flight controller that uses GPS signals to maintain altitude and waypoint navigation.

The Tetracam ADC camera was also selected as the image sensor and installed in the front cargo chamber of the body of the Sig Kadet Senior airframe (Fig. 3).

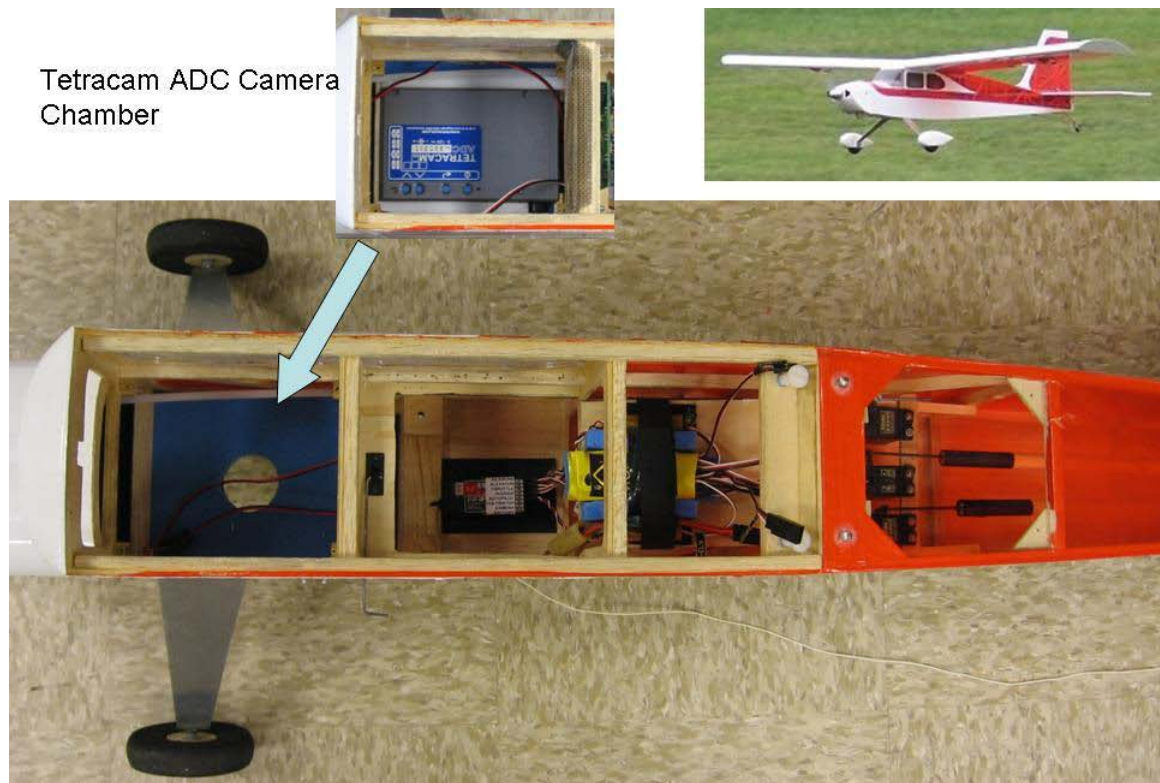


Fig. 3. Sig Kadet Senior UAV assembly and camera placement.

The UAV system was initially assembled at the United States Department of Agriculture (USDA), Agricultural Research Service (ARS), National Biological Control Lab (NDCL), and will be completely assembled at the USDA, ARS, Crop Production Systems Research Unit (CPSRU).

RESULTS AND DISCUSSION

Aerial Spray

Table 1 shows the statistical results of Uvitex concentration in hexane from monofilament line measurement for spray deposition downwind using Duncan grouping. The results illustrate that the two voltages of the DC power had significantly different impact on the spray deposition downwind, but the two release heights had no significant impact on the spray deposition. In average the pattern of the spray deposition downwind varied over the swath with the minimal value of $2.67 \times 10^{-5} \mu\text{l}/\text{cm}^2$ at the downwind distance 30 m and the maximal value of $5.36 \times 10^{-5} \mu\text{l}/\text{cm}^2$ at the downwind distance 36 m. Compared with other spray systems used for pest management, this sprayer delivered fair amount of liquid 40 m downwind in the 30 m swath with small droplet size (less than $50 \mu\text{m}$) (Huang et al., 2009).

Table 1. Uvitex concentration in hexane from monofilament line measurement using Duncan grouping*.

Votage (V)	Uvitex Concentration ($\mu\text{l}/\text{cm}^2$) (p=0.0079)	Downwind Distance (m)	Uvitex Concentration ($\mu\text{l}/\text{cm}^2$) (p=0.0304)
		0	$3.40 \times 10^{-5\text{ba}}$
4	$4.58 \times 10^{-5\text{a}}$	6	$3.15 \times 10^{-5\text{b}}$
6	$3.26 \times 10^{-5\text{b}}$	12	$5.31 \times 10^{-5\text{a}}$
Release Height (m)	Uvitex Concentration ($\mu\text{l}/\text{cm}^2$) (p=0.1305)	18	$3.77 \times 10^{-5\text{ba}}$
		24	$3.06 \times 10^{-5\text{b}}$
		30	$2.67 \times 10^{-5\text{b}}$
3.7	$3.56 \times 10^{-5\text{a}}$	36	$5.36 \times 10^{-5\text{a}}$
6.1	$4.29 \times 10^{-5\text{a}}$	42	$4.67 \times 10^{-5\text{ba}}$

* In the same column the quantity is not significantly different from the other one with the same letter.

Extractable Uvitex concentration from deposition on the spinners is presented in Table 2. Using the filament technique a higher concentration was observed compared to the spinner methodology. Measuring downwind coverage only a two-fold difference in deposition was observed, however using the spinner method a 30-fold difference in deposition was observed with limited statistical significance (p=0.1028). The model is not as significant as the one for monofilament line measurement. The results illustrate that the two voltages of the DC power had no different impact on the spray deposition downwind, and the two release heights had no too. In average the pattern of the spray deposition downwind varied over the swath with the minimal value of $7.24 \times 10^{-6} \mu\text{l}/\text{cm}^2$ at the downwind distance 6 m and the maximal value of $2.78 \times 10^{-5} \mu\text{l}/\text{cm}^2$ at the downwind distance 18 m. The inconsistency between the two spray measuring methods may be improved by adding more spinners downwind with higher measurement resolution.

Table 2. Uvitex concentration in hexane from spinner measurement using Duncan grouping*.

Votage (V)	Uvitex Concentration ($\mu\text{l}/\text{cm}^2$) (p=0.3053)	Downwind Distance (m)	Uvitex Concentration ($\mu\text{l}/\text{cm}^2$) (p=0.1028)
		6	$7.24 \times 10^{-6\text{b}}$
4	$2.44 \times 10^{-5\text{a}}$	18	$2.78 \times 10^{-5\text{a}}$
6	$1.77 \times 10^{-5\text{a}}$		
Release Height (m)	Uvitex Concentration ($\mu\text{l}/\text{cm}^2$) (p=0.2060)	30	$2.19 \times 10^{-5\text{ba}}$

3.7	2.52×10^{-5a}	42	2.73×10^{-5a}
6.1	1.69×10^{-5a}		

Aerial Imaging

SR20 carrying a video camera flew over an area in a runway in the riverside campus of Texas A&M University in College Station, Texas. The following Linux shell script was used to predefine the flight paths with waypoint GPS coordinates executing using *flyto* command:

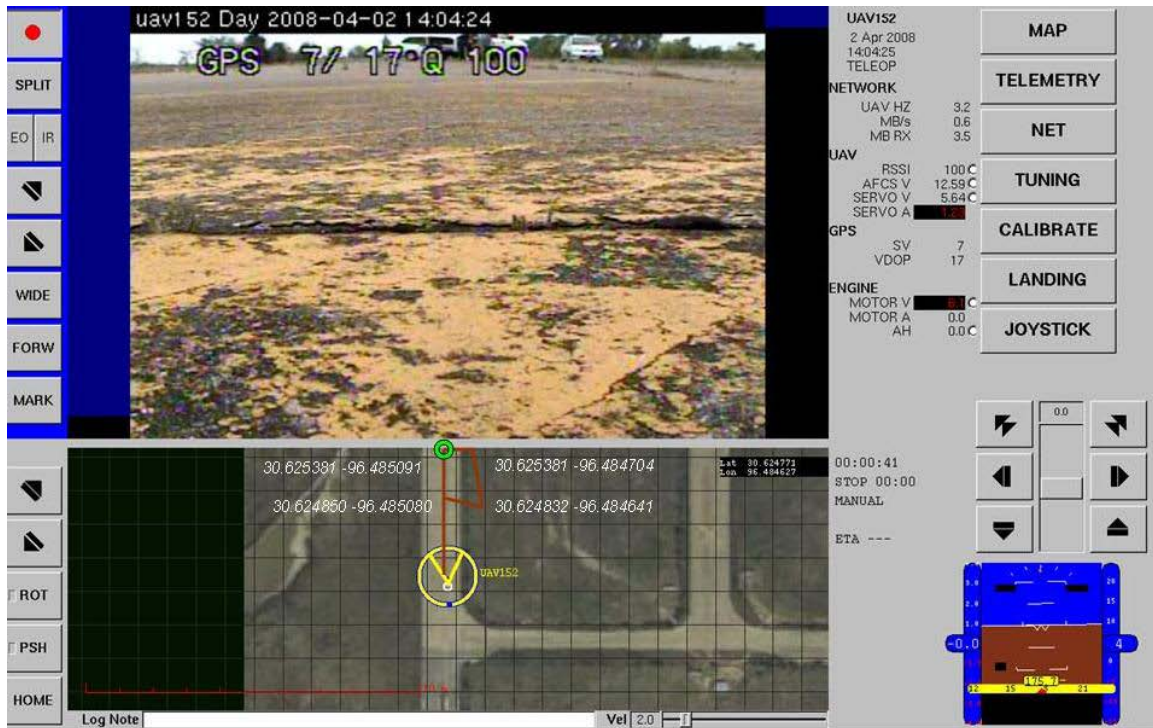
```
#!/bin/bash
```

```
uav=10.0.152.100:80
```

```
flyto -s $uav -t 3 -P -M 5 -m 7 -- 30.625381 -96.485091 0
flyto -s $uav -t -30 -P -m 4 -- 0 0 -20
flyto -s $uav -P -m 8 -- 14 1024 0
flyto -s $uav -t 3 -P -M 5 -m 7 -- 30.625381 -96.484704 0
flyto -s $uav -t 3 -P -M 5 -m 7 -- 30.624832 -96.484641 0
flyto -s $uav -t 3 -P -M 5 -m 7 -- 30.624850 -96.485080 0
flyto -s $uav -t -60 -P -m 4 -- 0 0 20
```

In the flight control system the commands in the script were implemented sequentially: the UAV took off and flew to (30.625381, -96.485091). At (30.625381, -96.485091) the UAV ascended 20 meters then executed the commands to actuate the servo that was installed on the pins 14 of the servo board B (-- 14) to trigger the camera. Then, at the same altitude, the UAV flew to the locations, (30.625381, -96.484704), (30.624832, -96.484641), and (30.624850, -96.485080). At (30.624850, -96.485080) the UAV descended 20 meters and headed back for landing. Fig. 4 shows the trajectory of the UAV in the lower frame of the gcs interface (UAV ground control software) with the preset waypoints in the shell script.

The Sig Kadet Senior UAV will fly over the crop fields located at Stoneville, MS (33°26'N, 90°55'W), at the USDA-ARS, CPSRU research farms in the summer of 2010 to detect the stress caused by shortage of water and damage of applied pesticide drift using the multispectral images from the Tetracam ADC camera.



— UAV waypoint trajectory ● Point to actuate servo

Fig. 4 GCS interface.

CONCLUSIONS

These field studies indicate that the UAV technology is useful for precision delivery of agrochemicals for crop protection and management. The ULV sprayer for the Rotomotion SR200 UAV helicopter was able to deliver liquid covering the 30 m swath, 42 m downwind. Deposition results from monofilament lines demonstrated that the spray coverage was sensitive to the power voltage but not release height. The deposition measurement from spinner methodology needs to be refined to achieve higher resolution and lower variance.

The Tetracam ADC camera was useful for collecting remote sensing data to identify and monitor crop stress, on either the Rotomotion SR20 UAV helicopter or fixed-wing Sig Kadet Senior. Integration of high-resolution remote sensing capability with ULV spray application will greatly expand the potential use of UAV technology for precision pest management. Except for our systems development on Rotomotion SR series UAV helicopters, the UAV systems are used for either spraying or for remote sensing. This research provides a prototype to further develop an integrated system for precision spraying directed by remote sensing on UAVs.

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