CHEMICAL ENGINEERING TRANSACTIONS

VOL. 44, 2015

A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Riccardo Guidetti, Luigi Bodria, Stanley Best

ISBN 978-88-95608-35-8; **ISSN** 2283-9216

DOI: 10.3303/CET1544052

Deployment and Performance of a UAV for Crop Spraying

Durham K. Giles*, Ryan C. Billing

Department of Biological & Agricultural Engineering, University of California, Davis, CA 95616 USA
dkgiles@ucdavis.edu

Small, unmanned aircraft systems (UAS) provide an opportunity for pesticide spray application in which the applicator can be displaced from close proximity of the spray discharge and in which the spray application can be made with highly targeted spatial resolution, particularly in challenging geographic terrain. In this project, a commercially manufactured UAS-mounted spray system was deployed in high-value specialty crops in California. The UAS used in this project was a unmanned aerial vehicle (UAV) and an associated ground control station that provided a means for remote piloting of the aircraft. The aircraft was a petrol-powered helicopter (RMAX, Yamaha Motor Co. USA, Cypress, CA USA) originally developed for spraying of rice fields in Asia. In this test, the primary experimental areas for spray deposition and performance assessment included a 0.61 ha block of Cabernet Sauvignon wine grapes located at the University of California Oakville Field Station in Napa County, CA USA. The block consisted of 42 rows, each 61 m long with a row spacing of 2.4 m. Depending on the spray method deployed, specifically, the swath width used and the flight pattern flown, the UAS spray application could achieve 2.0 to 4.5 ha/h work rates while applying volume rates of 14.0 to 39.0 L/ha. Spray deposition on the grape foliage increased with applied volume rate. In comparisons to ground-based sprays at 935 L/hr, deposition in the grape canopy from the UAS at 47 L/ha was similar.

1. Introduction

Unmanned aerial vehicles (UAV's) are operated remotely either by telemetry, where the operator maintains visual contact with the aircraft or autonomously along preprogrammed paths using GPS and inertial guidance. The initial uses in agriculture have been for remote sensing, with an emphasis on visual inspection of crop or field conditions and for tracking assets such as machinery, workers or product. UAS technology has utility in agriculture, forestry and vector control for not only observation and sensing but also for delivery of payloads, including application of agrochemicals.

The application of crop inputs such as fertilizers and pesticides by UAS presents an engineering design challenge where the payload and power demands from a spraying or granular applicator are significantly greater than those of low-mass, low-power cameras or sensors for inspection. Increases in the payload mass that can be carried on-board and dispensed leads to increased flight endurance and improved economic return.

Previous work has addressed the design of agricultural spray systems for small UAV's (Huang, et al., 2009) including specialized electrostatic rotary atomizers (Ru et al., 2011). The requirement for low volume application, in consideration of limited payload capacity, has been emphasized. Other work has investigated the use of multiple UAV's flying in coordinated fleets for spray application (Wang et al, 2013) and the development of on-board monitoring systems to aid the ground-based operator's situational awareness of the UAV's status (Sugiura et al., 2005).

The potential ease of deployment, reduction in operator exposure to chemicals and the improved ability to apply chemicals in a highly timely and highly spatially resolved manner make UAS spray application an attractive proposition from a technical viewpoint. However, there are concerns and limitations due to flight and chemical safety, potential environmental contamination, vehicle cost, flight endurance and payload constraints. Moreover, the regulatory treatment by aviation and environmental agencies remains unresolved. Spray deposition, vehicle suitability and work rate data are requisite to analyze the technical and economic

Please cite this article as: Giles D., Billing R., 2015, Deployment and performance of a uav for crop spraying, Chemical Engineering Transactions, 44, 307-312 DOI: 10.3303/CET1544052

feasibility of UAV deployment in agricultural spray applications, (Giles and Billing, 2014). This project addressed the feasibility of a small (100 kg) UAV for spray applications in specialty crops (vineyards and orchards) in California. A commercial UAV was used to spray crops and the work rate and spray deposition measured for a number of spray techniques and spray volume application rates.

2. Objectives

The objectives of this work were to:

a) Deploy an unmanned aerial vehicle for spraying a commercial scale vineyard under production conditions;

b) Develop, within the payload and range limitations of the UAV, a series of spray techniques to apply a range of liquid volume rates (l/ha); and,

c) Assess the resulting spray deposition and work rate of the UAV spray application.

3. Methods and Materials

The UAS used in this project was a commercially-produced UAV with the associated ground control station. The aircraft was a petroleum-powered helicopter (Model RMAX, Yamaha Motor U.S. Co. USA, Cypress, CA USA) originally developed and deployed for spraying agrochemicals onto rice in Asia (Figure 1). The physical characteristics of the aircraft where: Vehicle mass = 100 kg; Rotor diameter = 3.1 m; vehicle length = 3.6 m and vehicle height = 1.1 m. The aircraft power plant was a two-stroke, 250 cm3 displacement, liquid cooled, 13.6 kW engine. Control of the aircraft was through a radio linked, 60 mW, dual joystick handheld transmitter operating in the 72 MHz band. The model used in this project hd no provisions for autonomous operation; operation was by direct operator manipulation of the flight control surfaces and the engine throttle. Operation of the aircraft was limited to a 400 m line-of-sight range. The manufacturer's operational requirements and the U.S. Federal Aviation Administration specified that all operations be conducted with an independent, qualified observer positioned to monitor the location and movement of the aircraft at all times. Therefore, both the operator and the observer maintained visual contact with the aircraft during all testing.

Figure 1. Unmanned aerial vehicle (UAV) used in this project; shown with qualified operator and observer.

All flights and testing of the UAS were conducted under a Certificate of Authorization or Wavier (COA) issued by the United States Federal Aviation Administration (FAA). Currently, there are extremely limited provisions for legal commercial flights of UAV's in the United States. Certificates of Authorization are issued exclusively for public agency use; the COA for this project was issued to UC-Davis for agricultural spraying, in accordance with specific limitations to the aircraft and in accordance with United States Federal Aviation Regulations Part 137, which regulates aerial agricultural applications. The terms of each COA specify the aircraft that can be flown, the geographic areas in which the aircraft can operate and the conditions of operation. Current rules on COA’s also require that the pilot and the observer be qualified, tested pilots for manned aircraft and also hold an FAA Class II Medical Certificate. Flights were limited to an area within a radius of 1.8 nm around the vineyard test site (38.429219° N, 122.410564° W) and all flights were limited to areas greater than 9.1 km from any airports and limited to daylight hours and in Visual Flight Rules (VFR) conditions. All flights were conducted in Class G airspace, as defined by the International Civil Aviation Organization (ICAO).

The field test area for initial spray deposition and performance assessment was a 0.61 ha vineyard located in Napa County, CA USA. The block was configured as rows 61 m long with a spacing of 2.4 m; there were 42 rows in the block. To determine the spray application rate (in L/ha) and the sprayer productivity or work rate (in ha/hr), the aircraft was deployed to spray the test field in the same manner that would be used to treat the field in commercial operations. During the spray process, the time and motion of the aircraft was monitored and recorded by visual monitoring and through on-board two video cameras with time-stamped records. The time spent spraying each pass, repositioning the aircraft at the end of each pass, ferrying the aircraft from the loading site to the test field and the time spent refilling the aircraft were all recorded. During the spray tests, the water sensitive paper (TeeJet, Inc. Wheaton, IL USA) was positioned in the test block and was analyzed to estimate spray deposition.

Additional spray deposition was determined by tracer analysis of sprayed foliage. In the tracer study, the aircraft was configured in two different spray system configurations. In configuration A, two flat fan nozzles (8002XR, TeeJet, Inc., Wheaton, IL USA) were placed on the spray boom and operated at approximately 300 kPa. In configuration B, three flat fan nozzles (8001XR, TeeJet, Inc., Wheaton, IL USA) were placed on the spray boom and operated at approximately 300 kPa. In both cases, the aircraft was flown at 3-4 m above the canopy and the speed was approximately 20 km/h (Figure 2). An on-board spray application controller adjusted the spray pressure, and consequently, the liquid flow rate to maintain the target volumetric application rate of 47 l/ha. The spray deposition achieved by the two configurations of the UAV were compared to the grower “standard” ground spray application using a typical airblast sprayer applying 935 l/ha at a ground speed of 3.5 km/hr and hollow-cone nozzles operating at 750 kPa.

Figure 2. Unmanned aerial vehicle (UAV) spray pass over vineyard as viewed by aircraft operator

Metallic spray tracers were used to quantify the spray deposition. The tracers used were cobalt (Co), molybdenum (Mo) and manganese (Mn) for the ground spray, the UAV configuration A and UAV configuration B, respectively. Cobalt was applied in a tank mix concentration of 200 ppm while the UAV applications were at a tank mix concentration of 4,000 ppm. When coupled with the 935 l/ha tank mix application rate of the ground sprayer and the 47 l/ha UAV tank mix application rate, the applied mass of each elemental tracer per ha was equivalent.

Post spraying, leaves were sampled for chemical analysis to quantify the deposition of each element (Co, Mo and Mn), representing the deposition from each spray method. Pre-treatment samples were also collected and analyzed to determine the background (pre-spray) levels of each element. Background levels of each tracer were subtracted from the post-spray samples to determine the mass of each tracer added to the leaves by the spray deposition. Two types of leaf samples were collected. The first set of samples were leaf punches taken from the centre of leaves. The punches were 2.5 cm in diameter and 100 punches were collected per sample. Punches were collected directly into an ethanol-washed sample bottle, sealed and refrigerated. The second set of samples were collected as entire leaf "grab" samples and placed into polyethylene zip-seal bags and refrigerated. All samples were kept refrigerated until delivery to the University of California Agricultural and Natural Resources Analytical Laboratory in Davis, CA. The elapsed time from sample collected to lab delivery was approximately 4 hours. Samples were dried and then analyzed for total mass concentration of each tracer.

4. Results

As discussed by Giles and Billing (2014), the application rate was determined directly by volumetrically measuring the actual liquid discharged from the aircraft while the spraying the known land area of the test vineyard. Results for the four flight patterns (viz., swatch width and passes per swath) are shown in Table 1.

Table 1. Spray application rate as determined by swatch width and number of passes per swath

Number of rows treated in swath (width in m)	Number of spray passes per swath	Resulting application rate (l / ha)
2 (4.8)	2	39.03
2 (4.8)	1	19.76
3 (7.2)	2	29.20
3 (7.2)	1	13.99

As expected, spray work rate, or productivity, decreased as application rate increased, due to more time spent flying the aircraft within the field and more time spent ferrying and refilling the aircraft. Achieved work rates, for the four flight patterns, are shown in Table 2.

Table 2. Spray work rate, or productivity, as a function of the spray flight strategy, viz., swath width and number of passes per swath

Number of rows treated in swath (width in m)	Number of spray passes per swath	Resulting work rate (ha hr^{-1})
2 (4.8)	2	2.02
2 (4.8)	1	3.69
3 (7.2)	2	2.68
3 (7.2)	1	4.50

In the initial spray field testing, the spray deposition was determine by image analysis of water sensitive paper placed in the vineyard foliage. The results allowed the analysis of spray data in a novel method (Giles and Billing, 2004) in which the relationship between field work rates and resulting spray deposition was visualized (Figure 3). Spray deposition, as estimated by water sensitive card analysis, was found to decrease as work rate was increased. Using the relationship shown below, an applicator could select an application pattern based on the requisite spray deposition.

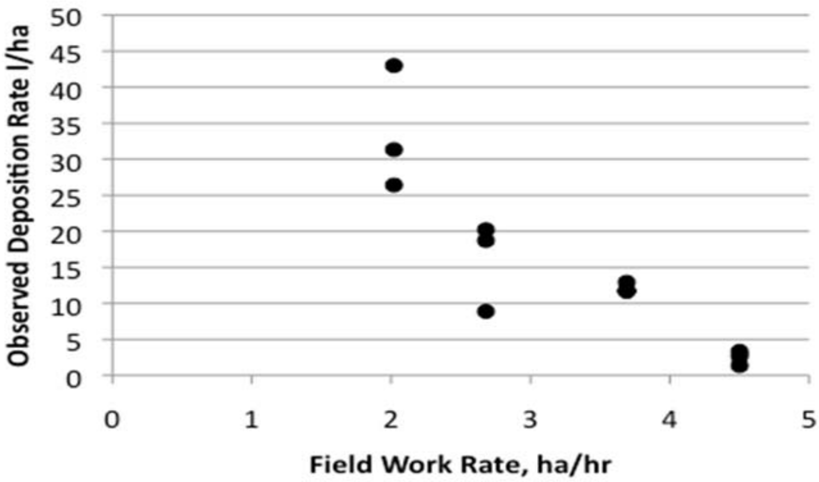

Figure 3. Observed relationship between spray deposition rate (water sensitive paper) and field productivity rate in multi-load spray tasks

Subsequent to the field testing reported above, the liquid delivery pump on the aircraft was replaced with a higher capacity pump such that 47 l/ha application rates could be achieved. The elemental tracer studies were conducted with the improved spray system, that is, a 47 l/ha application rate achieved with the 2-row swatch, two-pass spray configuration. The spray deposition results are shown in Table 3. Samples were collected in the top (>1.5 m), middle (1 to 1.5 m) and bottom (< 1 m) elevations in the canopy.

Table 3. Spray deposition comparisons using metallic tracers applied at constant mass per land area rates using two UAV configurations and a "grower-standard" ground-based application method. Standard deviations in parentheses.

Canopy location	Sample type	Ground sprayer 935 L/ha tracer (ppm)	UAV - Sprayer A 47 L/ha tracer (ppm)	UAV - Sprayer B 47 L/ha tracer (ppm)
Top	Leaf punch	38.18 (8.91)	56.32 (2.63)	38.17 (8.50)
Middle	Leaf punch	74.18 (10.53)	43.69 (3.97)	50.92 (10.21)
Bottom	Leaf punch	87.90 (20.06)	52.14 (2.29)	54.92 (4.43)
Top	Leaf grab	30.57 (5.26)	88.54 (6.69)	70.00 (10.12)
Middle	Leaf grab	69.13 (18.45)	63.90 (10.19)	73.00 (17.90)
Bottom	Leaf grab	100.10 (21.91)	70.13 (1.41)	82.00 (17.04)
Average	All	66.68 (28.31)	60.78 (15.05)	59.57 (18.18)

5. Conclusions

The experimental results from this field work supported the following conclusions. Firstly, that unmanned aircraft systems can be successfully deployed in specialty crop spraying conditions. The aircraft performed with no mechanical or operational failures or unanticipated events. Secondly, spray application rates on the order of 10 to 50 l/ha can be achieved through manipulation of the flight patterns and effective swath width. Moreover, the aircraft spray system can be improved through engineering of higher volumetric output pumps. Thirdly, effective spray work rates of 2-5 ha / hr can be achieved, even considering the limited payload and range of the aircraft. Also, an improved version of the aircraft, with a higher payload capacity is in development; this would improve field work rates by reducing the number of ferry/reload cycles per land area treated. Fourthly, spray deposition rates of 10 to 40 l/ha can be achieved; however significant variability in deposition can be present. These spray deposition rates are similar to those achieved by manned aircraft operating in similar conditions. Fifthly, that spray deposition (of tracer simulating active ingredient) from the aircraft can be similar to that observed from a standard “grower” ground-based spray application. Finally, it was observed that operator training and skill are critical for unmanned aircraft spraying; however, use of on-board vehicle stabilization systems and aided by autonomous operation, can reduce operator work load and required skill.

The results from this study provided insight into the potential commercial deployment of unmanned vehicles for specialty crop spraying in a high value crop environment. Spray application rates and resulting deposition rates were comparable to those typically observed in manned aerial spraying. Sprayer work rates achieved were in excess of those typical with ground-based vehicle spraying in grape production. Therefore, in the tested conditions, UAV spraying could provide hybrid performance that includes beneficial aspects of both manned aerial spraying (high work rates) and ground-based spraying (ease of deployment).

Acknowledgements

This study was conducted using resources provided by the Agricultural Experiment Station, University of California, Davis. The support and UAV loan of Yamaha Motor Company U.S. is appreciated. Appreciation is expressed to Mike Anderson and the Oakville Field Station of the Department of Viticulture and Enology at the University of California, Davis.

References

Giles, D.K., Billing, R., 2014, Unmanned aerial platforms for spraying: deployment and performance. Aspects of Appl. Bio., 12, :63-69.

Huang Y., Hoffmann, W.C., Lan, Y., Wu, W., Fritz, B.K., 2009, Development of a spray system for an unmanned aerial vehicle platform. Appl. Eng. in Ag., 25, 803-809.

Ru Y., Zhou, H., Fan, Q., Wu, X., 2011, Design and investigation of ultra-low volume centrifugal spraying system on aerial plant protection. Paper No. 11-10663, American Society of Agricultural and Biological Engineers. Presented at Louisville, KY USA.

Sugiura R, Ishii, K., Noguchi, N., 2005, Development of monitoring system to support operations of an unmanned helicopter. Paper No. 05-1019, American Society of Agricultural and Biological Engineers. Presented at Tampa, FL USA.

Wang Z, Lan, Y., Hoffmann, W.C., Wang, Y., Zheng, Y., 2013, Low altitude and multiple helicopter formation in precision agriculture. Paper No. 13-1618681, American Society of Agricultural and Biological Engineers. Presented at Kansas City, MO, USA.