Precision Weed Spraying using a Multirotor UAV

Lucas J. de Rijk, Seumas M. Beedie, and Karl A. Stol*
Department of Mechanical Engineering, University of Auckland, New Zealand

ABSTRACT

This paper presents a method for integrating spraying components on a multirotor Unmanned Aerial Vehicle (UAV) in order to perform aerial precision weed spraying. Experimental tests were conducted to assess spray accuracy as a function of tracking dynamics, target position, and UAV motion during manual flights. It was found that high standard deviations of UAV roll and pitch are correlated with poor spray performance and that the implemented system is robust to light wind exposure.

1 INTRODUCTION

Over the past several decades, there has been proliferation and acceptance of emerging technologies in the agricultural industry, particularly relating to Unmanned Aerial Vehicles (UAVs) [1,2]. Improved technology of multirotor UAVs has attracted research on the ability to carry out high precision agriculture-related tasks. One such application is the spraying of weeds, which is of vital importance for crop yields, but can be either time consuming in the case of manual spot-spraying, or expensive and environmentally harmful in the case of boom spraying [3]. While existing UAVs offer blanket spraying of crops, the advantages of these systems over land-based boom spraying are limited. In contrast to ground-based autonomous spraying, an airborne system is faster and not reliant on a traversable surface.

Utilising a visual tracking system enables an autonomous weed spraying platform to both distinguish weeds from surrounding crops and pasture, as well as track the position of a target weed during flight to enable accurate spraying. There is significant previous work [4] relating to the visual identification of weeds from high altitude, but these methods are unsuitable for high speed control scenarios due to high latency and high processing power requirements [5]. Hansen et al. [6] used a medium altitude aerial visual system and global positioning satellite waypoints to direct the movement of a ground-based spraying system, with a Time of Flight (ToF) camera identified as a potential method for identifying weeds at close range, capable of framerates of 30fps, which may be sufficient for controlled tracking.

Investigation into aerial spray systems has been limited, with commercial products utilising wide swathes for crop dusting [7], and academic research focusing on low precision wide coverage spray systems [8] with a root mean square (RMS) error of 0.2m from at an altitude of 5m. In order to precisely spray common herbaceous weeds such as Californian thistles, which have an average diameter of around 110mm [9], a lower altitude and less diffuse spray will be required.

This paper investigates the control system requirements and capabilities for precision weed spraying using a UAV, by first describing the hardware used for testing, followed by an overview of the implemented control system and its characteristics. Finally, the precision of the spraying performance is assessed in flight.

2 EXPERIMENTAL HARDWARE

The experimental system is shown in Figure 1. The UAV is an Aeronavics BOT quadcopter with a motor-to-motor diameter of 1.0 m and flight endurance of 10 minutes when carrying the 1.2 kg spraying system. The Foxtech 3-axis gimbal directs

*contact email: k.stol@auckland.ac.nz

the spray and dynamically isolates the camera and nozzle from UAV attitude changes. The Foxtech gimbal uses an AlexMos 32-bit gimbal controller with two inertial measurement units (IMUs) in order to stabilise the camera and allows inputs to control the gimbal axes.

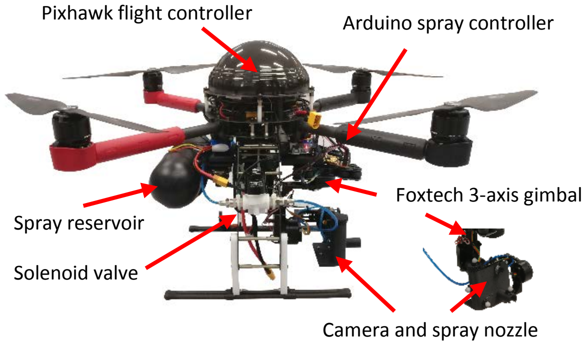


Figure 1 - Multirotor UAV with spray system

For the purposes of this study, accurate weed identification was not necessary, as experiments could be carried out with any visual tracking system with sufficient sampling frequency to allow control goals to be met. The CMUcam5 Pixy is suitable as it allows hue-based visual tracking at 50fps using a resolution of 320x200 pixels and vertical and horizontal fields of view of 47° and 75° respectively. Existing experiments of the Pixy camera implemented for visual tracking on UAVs [10] showed that using the visual input to directly control UAV motion was not an effective method of tracking, resulting in large overshoot and slow transient response of 2-4 seconds. These results support the use of a pan/tilt gimbal for the purposes of visual tracking, which have been used to achieve errors of less than 10 pixels [11].

In place of a weed, bright red targets printed onto paper were used to provide a high contrast against the laboratory floor background, allowing consistent visual identification as well as enabling visual analysis of the result of each test to quantify spray performance. While some phenomena such as liquid splashing and spreading over the ground are not emulated correctly using a flat target, this experimental setup does provide a useful measurement of spray accuracy.

An Arduino Mega 2560 was used to implement a controller that utilizes feedback from the Pixy camera and provides output to the gimbal controller and solenoid spray valve. The Arduino was also used to receive supervisory input from a smartphone over Bluetooth.

3 CONTROL SYSTEM IMPLEMENTATION

A spherical coordinate system, Figure 3, is used to describe the target location relative to the camera frame. The horizontal pixel error measured by the camera is used to measure azimuth angle and the vertical pixel error measured by the camera is used to measure elevation angle.

Figure 3 illustrates the controller for the gimbal yaw axis, for regulating azimuth angle Ψ. The controller for the gimbal pitch axis, to regulate the elevation angle ϑ, is identical in structure, whereas the roll controller does not have a visual feedback loop because a change in the gimbal roll axis does not result in a change in spray direction.

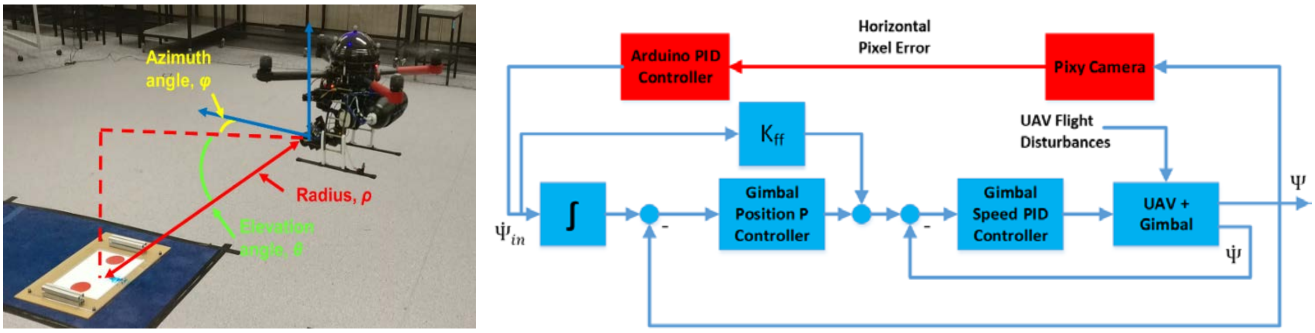


Figure 3 - Target coordinates and control system block diagram for azimuth tracking

Shown in blue in Figure 4 is the gimbal control system using cascade position and speed controllers. It allows a user to give a speed control input, which correspondingly adjusts the position setpoint at which the gimbal is stabilised, as well as giving a direct speed adjustment using a feedforward gain. Shown in red in Figure 4 is the added vision feedback loop, which provides a velocity control signal to the gimbal calculated using a PID controller based on the pixel error between the centre of the frame and the target centroid. PID gains and sampling frequency are adjustable through the alteration of the Arduino program.

The implemented PID controllers were tuned heuristically, with the aim of improving the disturbance rejection of the system as much as possible, without introducing oscillation in response to a large step input which occurs when a target is introduced at the edge of the image frame.

4 SYSTEM CHARACTERIZATION

4.1 Closed-Loop Frequency Response

The closed-loop frequency response of the tracking system was determined through the use of a VICON motion capture system. Motion capture markers were attached to the camera and target, and the UAV was moved by hand for two minutes with the tracking system operating, with the goal of providing a wide range of excitation frequencies.

Transfer functions were then approximated for each of the two relevant directions using the input data (the azimuth and elevation angles) and the output data (the yaw and pitch angles of the camera respectively). These transfer functions were used to determine the closed-loop frequency response, Figure 4. The corner frequency is 0.78Hz for the yaw axis, and 1.48Hz for the pitch axis. The difference in corner frequency is likely due to the system having greater rotational inertia about the yaw axis.

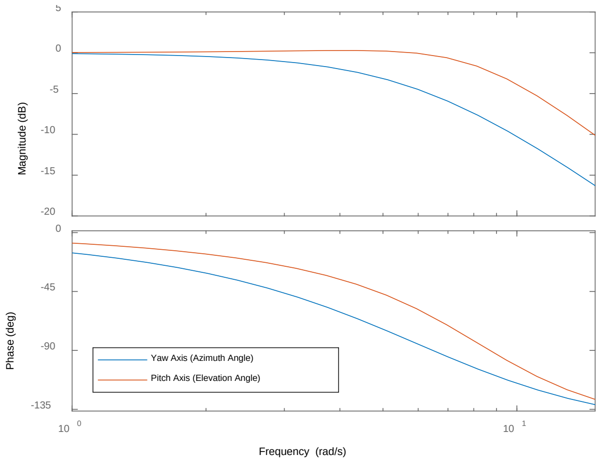


Figure 4 - Bode plot for gimbal yaw and pitch

A spectral analysis using the Fast Fourier Transform was carried out on the azimuth and elevation angle data collected during later flight tests (see Section 5) for the two flights with the highest UAV roll and pitch standard deviation respectively. It was found that the majority of excitation angle change occurred at frequencies of less than 0.5Hz as shown in Figure 5. However, as spray performance did appear to be negatively impacted at these levels of roll and pitch standard deviation, it is unlikely that the corner frequency is an accurate measure of the excitation frequency below which spray performance will not be negatively affected.

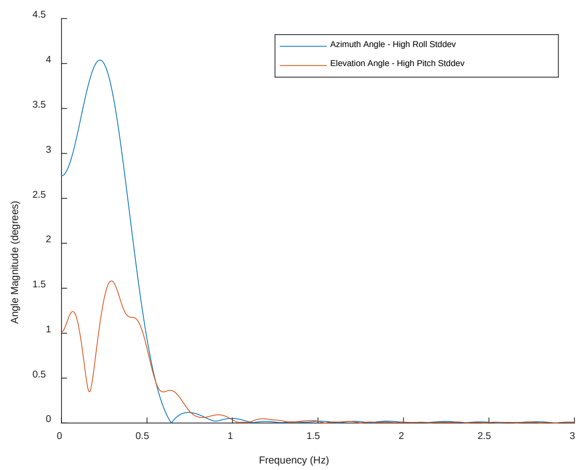


Figure 5 - Frequency spectrum of flight test data

4.2 Effect of Sampling Frequency

A study was carried out to determine how corner frequency degrades with reduced sampling frequency. This was achieved by sampling the camera at reduced frequencies, and again determining the closed-loop frequency response as in section 4.1. To reduce the number of variables changing between tests, excitation was only provided in the yaw direction and the target was moved instead of the UAV to avoid the gimbal needing to correct for changes in UAV orientation. To gain a more accurate estimate of the corner frequency at each sampling frequency, transfer functions of up to fifth order were fitted to the data, and the convergence of these fitted functions, Figure 6, was used to establish the actual corner frequencies. The data does support the overall expected trend that increasing sampling frequency results in a higher corner frequency, but there is uncertainty present in the graph such as the unexplained local minimum at 40Hz sampling frequency. This may be due to the limited duration of the tests, as well as non-uniform excitation signals between trials which may have resulted in less data at some frequencies. Corner frequency does not seem to be significantly affected until below sampling frequencies of 30Hz. For comparison, template matching techniques have been able to achieve sampling frequencies between 26Hz and 29Hz using a small form factor PC/104+ for processing [12].

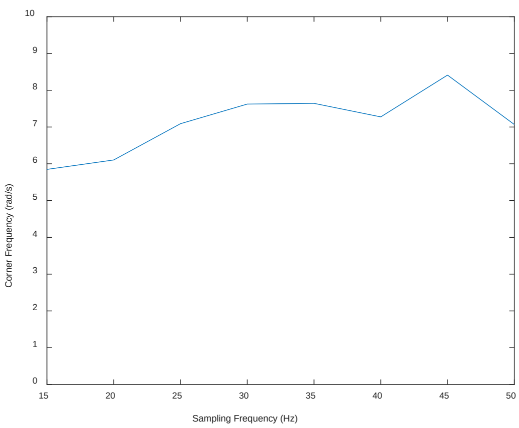


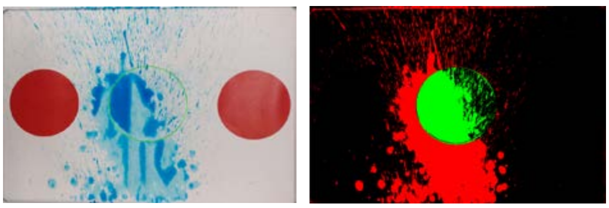
Figure 6 – Effect of sampling frequency

4.4 Spray Duration

A study was carried out to determine the ideal duration of the spray in order to provide high coverage of the target without unnecessary spillage beyond the edge of the target. This spray duration refers to the total amount of time for which the solenoid valve is open. If the pixel error exceeds a 10-pixel threshold while spraying, the spray will be interrupted, and will only resume when the pixel error drops back within the acceptable range. It was found that any spray duration exceeding 1.1 seconds would increase spillage without increasing coverage, so a 1.1 second spray duration was used for all flight tests. In all tests the fluid reservoir was pressurised to 100kPa, corresponding to a spray velocity of 7.5m/s at the nozzle.

5 FLIGHT TESTS

Spray performance was measured by using blue dyed water as a spray liquid, in conjunction with a computer vision analysis. Rather than spraying a coloured target directly, the mean position of two red targets on a sheet of paper was tracked, with the target spray area being a 110mm diameter circular outline between the two red targets, Figure 7(a). Photos were taken of the result of each spray test and an OpenCV program was written to measure the *coverage* (expressed as a fraction of the target circle covered with spray) and the *spillage* (area outside the circle covered with spray, also expressed as a fraction of the target area). Computer analysis of a typical spray test showing coverage in green and spillage in red can be seen below in Figure 7(b). This particular test had a coverage of 0.76 and a spillage of 2.06.



(a) (b)

Figure 7 - Spray test sample: (a) raw image (b) image analysed in OpenCV

5.1 Effect of UAV Movement

A total of 26 independent flight tests were carried out using a human pilot rather than an automated flight controller to provide with a wide range of UAV motion patterns. Variables considered in the analysis were the mean and standard deviation of range, elevation angle, and azimuth angle, as well as the standard deviation of roll, pitch, and yaw. A statistical analysis was undertaken to find which variables had the most significant effect on coverage and spillage.

The strongest relationship encountered for coverage involves UAV pitch standard deviation. A linear fit to this data, Figure 8, explains 44% of variation in the data. This trend likely exists because UAV pitch causes both the range and elevation angle to change. High pitch amplitudes result in higher amplitude and frequency changes in range and elevation angle, which the tracking system cannot reject effectively.

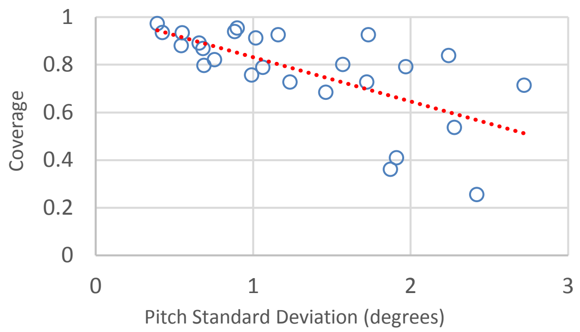


Figure 8 – Coverage vs UAV pitch variation

The second strongest relationship encountered for coverage was a negative relationship between UAV roll standard deviation and coverage, due to the gimbal being located below the UAV centre of mass.

To give an idea of the significance of these relationships, it was found that for the 12 tests where both roll and pitch standard deviation were less than 1°, the mean coverage was 87.7% of the target, compared to a mean coverage of 77.6% across all 26 flight tests.

There was no significant relationship between spillage and any of the measured motion variables. There was also no significant relationship found between target range and coverage, Figure 9, up to the maximum tested range of 2.2m.

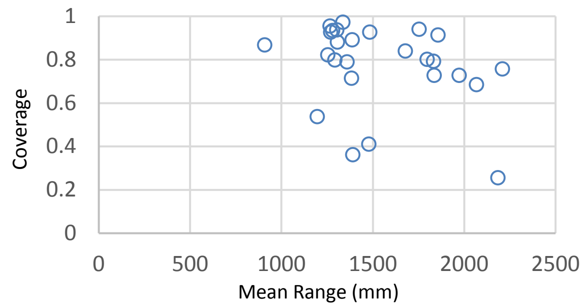


Figure 9 - Coverage vs target range

5.2 Wind Disturbance

Turbulent wind was introduced using two 540mm diameter fans, positioned such that they would influence both the UAV and the spray. A perpendicular cross-wind was tested as it was deemed the most likely to negatively influence the spray performance. The windspeed was measured using an anemometer to be an average of 4.0m/s at the UAV position, 2.2m/s across the spray path between the centre of the two fans, and 2.0m/s across the surface of the target, corresponding to a light or gentle breeze on the Beaufort scale.

Two flights were conducted, resulting in a high coverage (91.2% and 97.6%) and a typical amount of spillage compared to the other tests (208.8% and 267.3%) as seen in Figure 10. Each data point represents an individual test. This indicates that the light wind exposure had little to no impact on the effectiveness of the system, despite high UAV roll standard deviations of 1.33° and 1.44° compared to a mean of 0.83° for the tests without wind exposure.

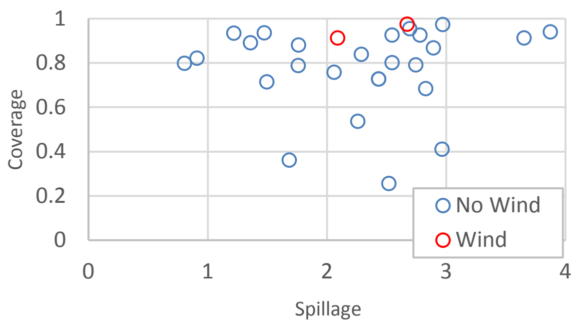


Figure 10 - Impact of light wind disturbances

6 CONCLUSIONS

An aerial precision spraying system has been developed utilising a gimballed sprayer and vision-based feedback for target tracking. Hue based tracking with a CMUcam5 Pixy simplified the vision system, and as such allowed a focus on the control requirements. The system was characterised using a range of tests and it was determined that the corner frequencies (baseband bandwidths) were 0.78Hz and 1.48Hz for the yaw and pitch axes respectively. It was also determined that these bandwidths are insensitive to sampling frequencies (vision frame rates) down to 30Hz.

Under controlled indoor conditions it was found that high UAV pitch and roll standard deviations were related to decreases in spray coverage. Flight tests with less than 1° of standard deviation of the UAV pitch and roll angles had a target coverage of more than 10 percentage points higher than the overall average coverage. Finally, two flight tests were carried out under exposure to light wind disturbance and it was found that this had little effect on the spray performance.

Future work could include the testing of the system outdoors using suitable station keeping controllers and the further development of weed tracking and identification from literature.

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