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Towards the development of an autonomous unmanned aerial system to collect time-stamped samples from the atmosphere and localize potential pathogen sources.

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Abstract

This paper presents the hardware development and testing of a new concept for air sampling via the integration of a prototype spore trap onboard Unmanned Aerial System (UAS). We propose the integration of a prototype spore trap onboard UAS to allow multiple capture of spore of pathogens in single remote locations at high or low altitude; otherwise not possible with stationary sampling devices. We also demonstrate the capability of this system for the capture of multiple time-stamped samples during a single mission. Wind tunnel testing was followed by simulation and flight testing was conducted to measure and quantify the spread during simulated airborne air sampling operations.

During autonomous operations, the onboard autopilot commands the servo to rotate the sampling device to a new indexed location once the UAS vehicle reaches the predefined waypoint or set of waypoints (which represents the region of interest). Time stamped UAS data is continuously logged during the flight to assist with analysis of the particles collected. Testing and validation of the autopilot and spore trap integration, functionality and performance is described. These tools may enhance the ability to detect new incursions of spores.

1. Introduction

There is a global need to develop technologies for earlier detection and monitoring of spores of plant pathogens EPP incursions (Aylor, 1990, 1999; Ingold, 1939; Watson, 2007). Through the absence of many pests and diseases commonly found overseas, Australia's plant industries have a valuable competitive advantage in terms of securing market access and maintaining lower production costs. Harmful plant pests and diseases can impact on food safety, trade, market access, market development and, ultimately, the profitability and sustainability of plant industries. Plant Biosecurity is designed to protect crops for these pests or diseases at national, regional or individual farm levels in Australia (Plant Biosecurity 2011).

This project is a scoping study to determine the potential of using an unmanned aerial vehicle (UAS) fitted with a spore trap, to detect and monitor spores of plant pathogens. We aim to develop a sampling system that will have the ability to spatially monitor fungal spores, and protocols to interpret their spatial distribution. This tool will greatly enhance the ability to detect new incursions of fungal pathogens and to enable more accurate the location of them. The technology will allow for earlier detection of EPP incursions in difficult areas and provide efficient and effective airborne surveillance.

Existing spore sampling devices are stationary at the sampling location. Location is important due to prevailing climatic conditions, and use of sampling devices in remote locations and where topography is severe is almost impossible. In such scenarios, airborne sampling has been suggested as a viable alternative (Aylor & Boehm, 2006; Zeller, 2007; Zhou, Ambrosia, Gasiewski, & Bland, 2009). Thus a new approach is desired which capability present to take spore samples in multiple locations and in remote regions where access to local sampling is difficult.

Previous research has shown the value of manned and unmanned systems for aerobiological sampling (Anderson et al., 1999; Corrigan, Roberts, Ramana, Kim, & Ramanathan, 2008; Dingus, 2008; Ingold, 1939; Peräjärvi, Lehtinen, Pöllänen, & Toivonen, 2008; Schmale, Dingus, & Reinholtz, 2008; Techy, Schmale, & Woolsey, 2010; Techy, Woolsey, & G., 2008). Dynamic sampling systems have the potential to improve upon current static ground based sampling methods. Autonomous UAS integrated with pathogen capture systems can allow for sampling in remote locations, provide corresponding spatial data to increase positional accuracy of samples taken, and undertake air samples in multiple locations for each predefined flight or ground mission.

Different remote sensing techniques have been used for environmental surveillance and spore sampling. For instance, LiDAR has been applied for carbon accounting and forest management (Patenaude et al., 2004; Rosette, North, Su, 2008) and Satellites analysis to measure the air quality (Cleugh, Leuning, Mu, & Running, 2007; Running et al., 1999). The main limitations of such systems are related to resolution and system cost (Berni, Zarco-Tejada, Suarez, & Fereres, 2009). Other approaches have been focused on the use of UAS for remote sensing and data collection. This field has been explored in areas related to vegetation management, control and power line inspection (Andersen, McGaughey, & Reutebuch, 2005; Emili et al., 2010; Guoqing & Deyan, 2007; Karim, Heinze, & Dunn, 2004). Conversely, UAS have also been used air sampling and environmental analysis. (Ligler et al., 1998) integrated a biosensor system on a small and remotely piloted airplane in order to collect aerosolized bacteria in flight, identify them and transmit the data on the ground. Nevertheless this system required human intervention for control and planning proposes.

A spore and pollen trap for use on aerial remotely piloted vehicles is described by (Gottwald and Tedders, 1985). The paper provides an excellent description of the design and test using a remotely controlled vehicle. On this research spores trap samplers were mounted between the fuselage and wing tips thus permitting time-stamping samples at different locations. The system used 180 degree servos, a molded plastic spore trap housing, and clear Melinex tape coated with adhesive. After spore sampling, the tapes were removed from drumps for microscope analysis. Spores traps and vehicle manoeuvring were activated and controlled remotely from the ground. This is groundwork showing the applicability of the spores trap on an aerial vehicle, but autonomous flight and geo-reference was not attempted by the authors. Kinematic conditions and airflow test were verified using and automobile test and no wind tunnel test was conducted or fan or pump was used. As will be described in this work this paper can be considered as an extension of that work by concentrating on introducing autonomous flight, wind tunnel test and monitoring kinematic conditions at UAS speeds using a pump.

Dingus et al. (Dingus, 2008; Schmale, et al., 2008;) have undertaken air sampling experiments using a UAS (Senior Telemaster model aircraft) where autonomous flight commands were provided by an autopilot system onboard. A total of four petri dishes were used on each UAV, two on each wing to undertake samples during flight. The petri plates were placed in each commanded by the UAS controller to open, take a sample then close to avoid contamination. This type of air sampling solution is limited to four samples during a single mission. Thus it cannot illustrate a multiple sampling as a function of time in different geographic areas. In other research, Anderson et al. (Anderson, et al., 1999) used a multi-channel fluorimeter and a custom ram-airdriven cyclone particle collector for air sampling experiments. Purified polycyclonal rabbit antibodies were fluoresced using fluorescent dye and dispersed in a predefined test area. The onboard fluorimeter (controlled by the ground station), provides real time detection of fluorescent particles in the atmosphere. This fluorescent technique has been used by several researchers in the community for particle detection (Ligler et al., 1993, Ligler et al. 1998, Sanders et al., 2001, Zhang et al, 2002). The use of particle counters/sizers onboard UASs provide an excellent method of real time identification of particles of known sizes in the atmosphere if the particles are present in large concentrations. Corrigan et al. (Corrigan, et al., 2008) performed a similar set of experiments, where total and optical particle counters where employed to detect black carbon concentrations over the Indian Ocean using autonomous UASs. The UASs were flown at a range of altitudes to generate a vertical profile of the atmospheric black carbon concentrations. However, pathogens are typically present in much lower concentrations, and not fluorescent. Thus, the most suitable method of pathogen detection is the collection and post processing of capture spore samples (by a trained plant pathologist).

Even though the literature on the use of UASs for aerial based sampling is limited, it has shown that UAS based sampling methods can improve upon static ground based techniques. Aerial sampling allows for the generation of vertical profiles of concentration levels, and can provide additional geo-positional information for captured samples. Additionally, the extended range of UASs can allow sampling to be undertaken over multiple remote locations.

The rest of the paper is organized as follows: section 2 describes the research methodology used for testing and validation of experiments justifying the reasons of using these approaches. Section 3 outlines the system architecture for the spore trap development as well for the UAS. Section 4 discusses wind tunnel testing results. Section 5 focuses on simulation and path planning. Section 6 describes autonomous flight testings. Conclusions are presented in section 7.

2. Research Methodology

In conducting work we try to answer this research questions: The amount of separate regions surveyed in a single mission and the endurance of the air sampling system (with the final airborne trap integrated onboard). Also, other questions relate the optimal flying manoeuvre in order to survey a single paddock and the planning for these manoeuvres given the large variation in terrain over the surveillance area. Moreover, we were also interested to know the accuracy in which the spores can be geo-located.

In order to answer these research questions we followed research methodology for the design, development, simulation and testing of the air sampling system. The following subsection presents an overview of the system requirements, testing and validation employed.

2.1. System Requirements

System requirement covers the definition of the payload and power requirements for the integration of the air sampling device with the UAS, this consideration will impact the research direction. Due the limitation of the UAV payload the weight of the system need to be less than 2 Kg. The dimensions of the systems are also limited to 121.5 mm x 117 mm (lateral). The device has to be powered by batteries for an endurance of at least one hour.

There were also several constrains related to the spore trap. The spore trap has to be designed so that there is no possibility of spores spreading to other parts of the sensor and therefore introducing error into the system's ability to be able to uniquely identify the paddock that the spores were detected in. This allows the authorities to quarantine the site to prevent further spread of the disease. In the case of a conventional spore trap, spores that come in under pressure can spread around the sensor drum and contaminate other parts of the sensor. This could result in an entire drum being contaminated even though the spores were present over a single paddock. This may create numerous false alarms. In order to the system has to be tested to determine the level of spread around the sensor drum. Furthermore, it has to be optimised based on minimizing the spread of spores around the sensor once they enter the collector under pressure. The system has to be designed to minimise probability of false alarm failure, and indicate that a diseased spore is present in a paddock when in fact it is not (possibly picked up en-route or on another paddock). In addition, the system has to be capable of surveying paddocks in a single 12 hour flying mission.

The research also seek data login requirements. In this sense the system has to be capable of accurate geo-location of detected spores. If a spore is trapped, it must be capable of indicating the position of the sensor at the time the spore was detected. All data collected during must be logged for post processing and visualisation.

2.2. Solution Development

The prototype spore trap was based on the Burkard design system (Cioffarelli & Natale, 2000). The main advantages compared to other sampling designs currently used for experimental airborne sampling include its simplicity and potential to capture multiple samples during a single mission. Additionally, the Burkard design has been used extensively for ground based sampling and spore capture, thus the airborne flying spore trap offers a design which has been thoroughly validated.

The developmental UAS platform is a Silverstone UAS airframe ("Flamingo Umanned Aerial Vehicle," 2009) with onboard autonomy and communications protocols developed by QUT and the Australian Research Centre for Aerospace and Automation (ARCAA).

2.3. Testing and Validation

It was found that wind tunnel experiments and flight testing were required to understand the modifications needed for the sampling sensor and to validate the spore capture performance of the prototype air sampling device and to ensure that multiple captured samples would not lead to overlap and subsequent contamination of individual samples inside the sensor and indexing system. Wind tunnel experiments were undertaken to calculate the approximate size of the sample captured on the tape at typical flight velocities of the test platform. The wind tunnel results were used to calculate the maximum number of samples which could be undertaken in a single flight test. Additionally, the wind tunnel testing was used for further optimisation of the spore trap design. Optimisation was aimed at minimizing the spread of the spores around the sensor once they entered the collector under pressure.

The wind tunnel results confirmed the spore traps capability to capture spores samples without contamination. The prototype air sampling device was integrated with the onboard UAS autopilot system and control hardware. The device was physically integrated with the UAS platform to undertake experiments over several proposed locations. This ensured that there was statistical significance to the results obtained, and demonstrated the repeatability of the flight testing methodology. Air sampling testing using the prototype spore capture device was undertaken in a semi-controlled flight test environment where ARCAA has clearance from CASA to undertaken autonomous UAS operations. The tests were conducted to demonstrate the spore capture performance of the UAS in real world conditions.

3. System Architecture

The following section provides an outline of the modifications undertaken on the prototype spore trap to make the device compatible with spore trap and UAS platform integration and testing. Figure 1 shows the spore trap system architecture. The system uses an autopilot, a ground control station, communication protocols and a modified spore trap sensor.

3.1. Prototype and Spore trap

As it was mention before this work is an extension of the research presented by (Gottwald and

Tedders, 1985) by concentrating on introducing autonomous flight, wind tunnel test and monitoring kinematic conditions at UAS speeds using a pump. However similar features such as the use of the spore trap were based on this work.

The Burkard design ("Volumetric Spore Trap," 2009) extracts air through a 14 x 2 mm slot and passes it over a strip of 'Melinex' tape coated with a gelatine solution (Schwartz & Billoski, 1990). On entering the trap the sudden change in direction of air causes particles with greater mass (the spores and other airborne materials) to adhere to the tape due to inertia. The tape is attached to a slowly rotating drum and the physical position on the tape indicates when the spores are collected. The conventional traps rotate over a one week period and the tape is removed for analysis in a laboratory.

The Burkard original dimensions and weight make it unsuitable for integration onto a small to medium sized UASs such as the UAS. Thus, there was a need to design a new hardware concept which meets the payload requirements for successful integration with the test platform.

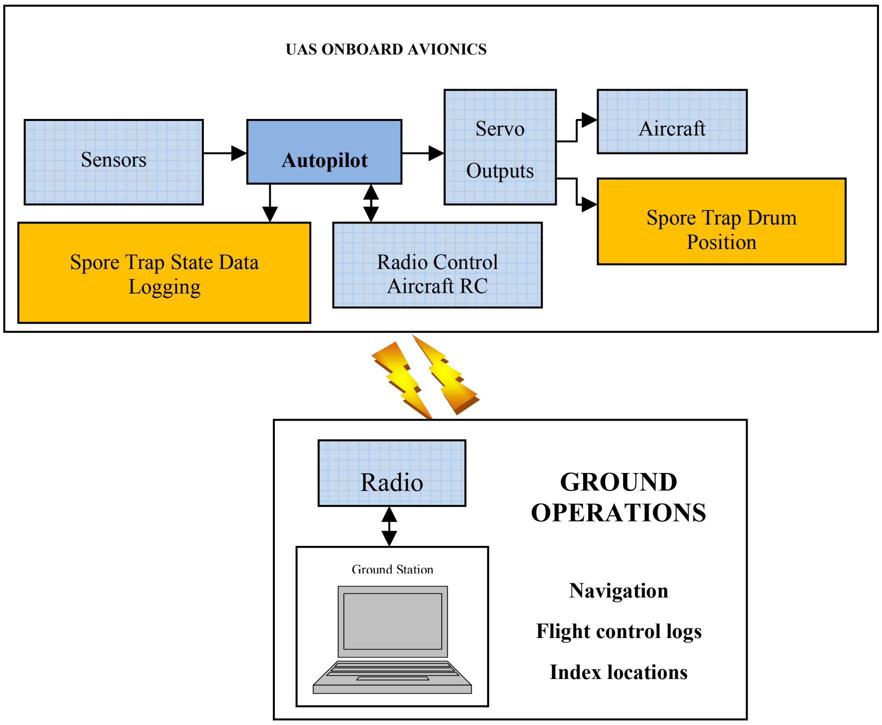


Figure 1. UAS Spore Capture System Architecture. The system uses an autopilot, a ground control station, communication protocols and the spores trap sensor.

A modified light weight version of the Burkard design which uses the sample principle of operation but employs a servo motor to control the position of the drum (Figure 2). This sections areas on the tape to correspond to geographical locations rather than intervals of time. The original design minimised positional errors caused by motor over run by using a servo with multiple turns and a gear ratio of approximately 3:1. The improvement in positional accuracy reduced the response time and therefore was replaced with a standard single turn servo for use in the UAS and subsequently for the ground based version of the mobile spore trap.

The air sampling concept involves the capture of spores on a Melanex tape, similar to the Burkard configuration. However, an onboard servo is commanded to move the tape index to a predefined location. This predefined location represents the spores captured over a known air sampling location. This concept allows for air sampling to be performed over multiple locations with the ability to geo-reference the samples. The number of samples which can be stored on a single tape is limited to the spread of the spores captured on the tape. Wind tunnel testing was conducted to measure and quantify the typical spread on the tape during UAS air sampling operations. The onboard autopilot on the test UAS platform was programmed to command the servo to move to a given indexed location once the UAS autonomously reached the predefined waypoints representing the region of interest. Time stamped UAS state data (e.g. GPS location, vehicle attitude, Tape Index) is logged during the flight to assist with analysis of the particles collected during flight.

3.1.1. Hardware Design Overview

The current hardware concept is based on the Burkard Volumetric Spore Trap (Volumetric Spore Trap, 2009). The Burkard Spore Trap (Figure 2) collects spore samples through a narrow orifice on the side of the device. 'Melinex' tape is used to trap spore samples travelling through the orifice. The tape spins at a predetermined rate (full rotation in 1 or 7 days) and trapped spore samples are analysed after the tape has completed a full rotation. In addition, a weather vane allows the spore trap to align itself with the wind direction and a pump is installed in the based to increase the air flow rate. The Burkard Spore Trap dimensions and weight make it unsuitable for integration onto small to medium sized UAVs such as the flamingo test platform (Flamingo Unmanned Aerial Vehicle, 2009). Thus there is a need to design a new hardware concept which meets the payload requirements for successful integration with the test platform in addition to high level project requirements (insert link/citation).

a) b) c)

Figure 2. a) Spore trap prototype concept with the following specifications: Length 218 mm, diameter 130 mm, a total mass of 1.5 Kg. Which were suitable to place it inside the UAS. b),c) Upper view of the spore trap including the Servo.

This section outlines the overall capability of the current hardware concept with respect to trapping spore samples. Due to the increased range of UAVs, An airborne sampling system has capability to take multiple samples during a single flight. A 'Melinex' tape configuration has been employed similar to that present in the Burkard. To avoid contamination between spore samples taken at different locations, a servo (Figure 2) has been connected to rotate the tape to a vacant location for each new spore sample taken.

During Radio Piloted Vehicle (RPV) flight, the mission commander must execute the tape rotation command when a new sample is to be taken. During autonomous flight, the tape rotation command must be given by the autopilot. A motorized pump (Figure 2) has been placed at the base of the hardware concept to force a given flow rate through the orifice. Currently, the motor does not have a load controller to adjust the flow rate. Onboard a UAV, the flow rate through the orifice will be a combination of the platform velocity and flow rate due to motor. To improve spore capture success, ideally, the air velocity at the orifice must be the same as the velocity of the

UAV. This may require the inclusion of a variable speed fan and a fan speed controller.

3.1.3. Proposed Hardware Design

The current hardware design requires modifications to meet the overall project goals and requirements. To successfully integrate the current hardware design onboard the flamingo UAV platform, some modifications are required. Since the current sensor is too large to fit within the front fuselage compartment it is required to install a modified canopy to the flamingo platform. Furthermore, Pulse Width Modulated (PWM) commands need to be given to the servo to rotate tape to the desired location. With the assumption that the sensor is a closed device, the flow rate can be used to calculate the air velocity through the orifice, hence a flow rate meter was used to measure the airflow through the device. In addition, a variable fan speed drive and controller is required to ensure that the velocity of air travelling through the orifice is the same velocity as the external airflow velocity. The canopy may not be required if the current sensor size is decreased to fit within the flamingo compartment.

3.2. Air Extraction System

To ensure that the new lightweight version was as effective at collecting spores as a Burkard spore trap airflow of greater than 10 litres per minute was required. The airflow experienced using the aerial system is well in excess of this value due to the forward velocity of the UAS therefore airflow may be only an issue for stationary or low speed ground based systems.

A new fan with a predefined flow rate was installed. The fan flow rate was calculated to ensure that the spore trap could maintain isokinetic conditions at the typical cruise velocities of the UAS Figure 3. Hence, by controlling the voltage, a known flow rate could be established for a given UAS airspeed Figure 4.

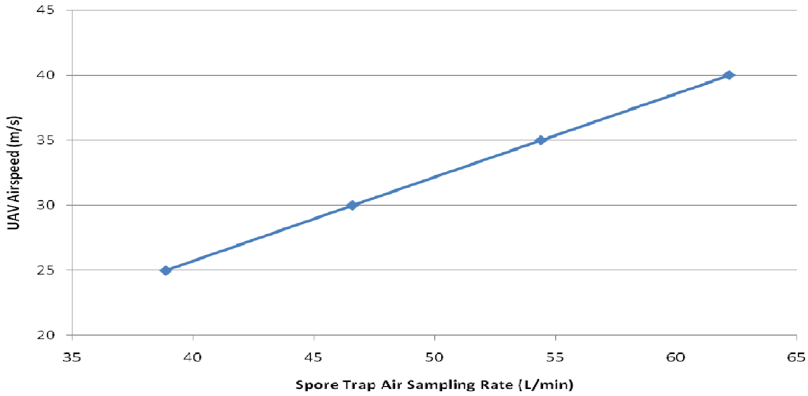


Figure 3. UAS Airspeed vs Spore Trap Air Sampling Rate for Isokinetic Conditions. The fan flow rate was calculated to ensure that the spore trap could maintain isokinetic conditions at the typical cruise velocities of the UAS.

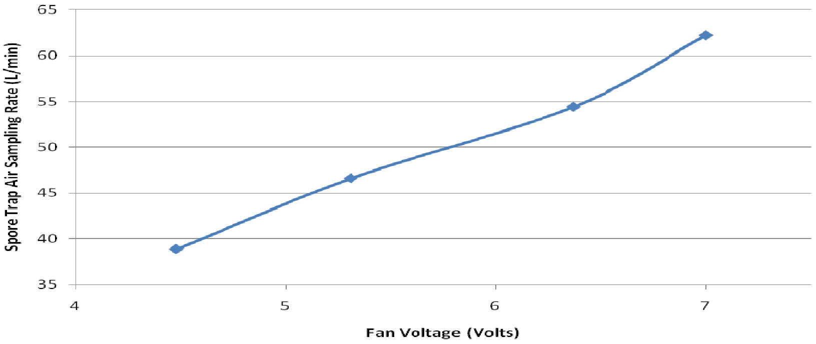


Figure 4. Spore Trap Air Sampling Rate vs Fan Voltage for Isokinetic Conditions. Controlling the voltage, a known flow rate could be established for a given UAS airspeed.

The modifications to the prototype spore trap enabled testing and validation during simulated (wind tunnel experiments) and flight tests. The following section provides an overview of UAS platform and autopilot systems used during of the flight tests.

3.3. UAS Platform Overview

The fully autonomous ARCAA/QUT UAS was selected as the test platform for this project. The UAS test platform is the Silvertone UAS airframe. Additional ARCAA developed avionics and communications systems that provide the necessary autonomous capabilities. The platform performance specifications had a range of up to 4Km from the ground station with speeds between 65 to 140 km/h (18-39 m/s), allowing a maximum endurance of 10 hours. In relation to the dimensions of the UAS it has a wing span of 4 meters with 2.9 meters legth and is able to carry up to 10 kg.

The Microilot 2128g autopilot system ("MicroPilot 2128g," 2009) provides autonomous capabilities to the ARCAA/QUT UAS platform. The Micropilot 2128g is a standalone solution which provides automated onboard navigational capabilities via integrated differential Global Position System (GPS) and gyroscopic sensors.

The flight plan configuration is uploaded by the mission commander to the ground control software Horizon, via the Human Machine Interface (HMI). Horizon provides the flexibility of modifying the flight plan online via a Graphical User Interface (GUI). The GUI was modified using the available Application Control Interfaces to include real time command and visual confirmation of the spore trap tape index.

A flight plan was created to include additional parameters to automatically shift the spore trap tape index to a new location so a new sample could be captured. This parameter value (representing the tape index) was read from a servo output pin and connected to the spore trap servo. To ensure that any potential spore trap servo malfunction would not affect UAS operations, the power to the spore trap servo was supplied from a separate battery and the commanded signal was isolated.

3.4 Drum Control and Geo-Referencing of Captured Spores

Before an autonomous operation is undertaken, a flight plan is generated and simulated using the ground station software. Waypoints (WP1 – WP6 in this case) are used as an example to represent the start and end locations of the region being sampled (Figure 5). Drum control was programmed into the flight plan through insertion of drum servo values which were synchronised to take place once the platform reached the sampling region.

The tape drum is set to a predefined initial location at the beginning of the mission. Once the UAS reaches the waypoint representing the start location of the mission flight plan, the tape index is programmed to rotate to the first sampling location (WP4). After the reaching the next waypoint (representing the end of the sampling region, WP5 in this case), the drum rotates to a neutral location to ensure that the sample currently collected is not contaminated. If multiple passes are required over a given region, the drum is programmed to rotate back to the first sampling location. This allows the aggregation of one sample over multiple passes to increase the overall volume of air sampled in the region of interest.

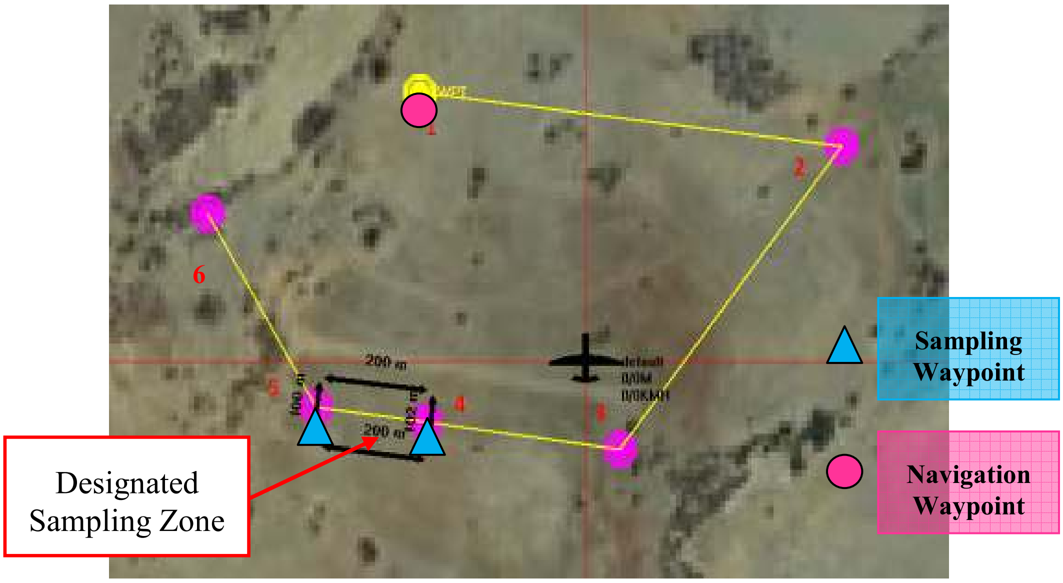


Figure 5. Ground station Visual Representation of Autonomous UAS Mission using the GUI from Horizon visualization software. In this image a region of 100 x 200 meters was designated as an aerial samping zone in the simulation.

In order to geo-reference the spore samples, time stamped UAS state data and spore trap tape index data is continuously logged throughout the duration of each flight location. This allows for generation of vertical flight profiles and visualisation and mapping of spores captured in particular regions.

4. Functional and Wind Tunnel Test

Functionality test were conducted to simulate the prototype spore trap operating as a stationary air sampling device and to provide reference values. The spore trap was tested for close and medium ranges, where simulated spore particles (sugar dissolved in distilled water and red food colouring) was dispersed using a smoke machine. White paper strips were used instead of Melanex tape to allow for visual verification of successful sugar capture.

4.1 Functionality Test

The spore trap and smoke machine were initially placed approximately 2m apart and the following tests were conducted for one minute each, the results are presented in Table 1 and correspondingly in

Table 1 - Close Range Test Results

Test Sample	Test type	Sampling Time (sec)	Voltage (V)	Spread (mm)
1	Close Range	60	0	2.5
2	Close Range	60	12	2.6
3	Close Range	60	7	2.8
1	Medium Range	300	0	N/A
2	Medium Range	300	12	2.0
3	Medium Range	300	7	1.5

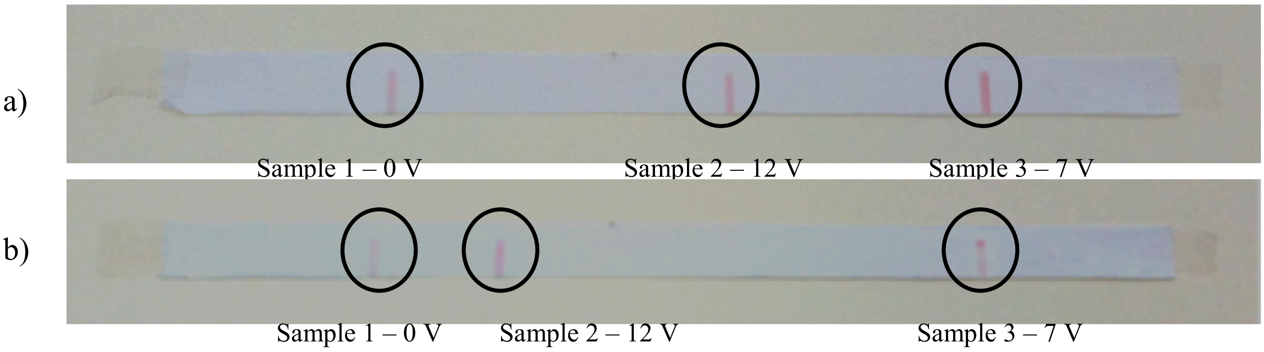


Figure 6. a) Close Range Field Test Results, b) Medium Range Test Results. In the following plots the voltage (V) is related to the pump rate (L/min). In this way the relation between the voltage and the pump rate is directly proportional, the higher the voltage the higher the pumping rate. The marks observed in each tape are the spores captured.

The spore trap and smoke machine were then placed approximately 20m apart and the following tests were conducted for five minutes each, the results are presented in and correspondingly in Table 1 and Figure 6. It should be noted that no simulated spores were captured for the test scenario where the spore trap internal fan was switched off (v=0).

The results show that as expected a higher sampling volume rate (spore trap sampling flow rate) generates a smaller spread. Additionally, increasing the distance between the smoke machine and spore trap resulted in a lower concentration of simulated spores captured. This was expected as the number of spores in the atmosphere once dispersed, will decrease in concentration over distance. It also defines the separation needed between samples so that there is no contamination between samples as the spore trap tape index rotates between locations.

The successful results of the field test indicate the possibility of the prototype spore trap to be used as an inexpensive alternative to other standalone stationary sampling devices as an effective airborne sampling system. However, in order to accurately simulate the airborne spore capture process, testing at similar velocities as those experienced by the UAS platform is required.

4.2. Wind Tunnel Testing

Tests were conducted to verify the validity of the proposed spore capture process. The aim of the wind tunnel tests was to simulate the spore trap process at the typical operational velocity of the UAS (Cox & Wathes, 1995; Wagner & Leith, 2001). The wind tunnel experiments were conducted to acquire the following results: number of spores trapped for a given spore density and exposure time, spore spread over tape for a given spore size and effect of flow stream velocity with respect to spores captured.

The following subsection provides an overview of the wind tunnel experiments used to quantify the spore traps performance in simulated flight scenarios.

4.2.1 QUT Wind Tunnel Testing

Two sets of test were performed: the first was using polystyrene polymers (PSP) dispersed through an atomizer, whilst the second one was using sugar dissolved trough a smoke machine and release them on a wind tunnel. A wind tunnel reduction was installed to produce typical operating velocities of the UAS platform (20-30m/s).

The wind tunnel setup consisted of six different components including the compressed air source, the atomizer, dryer filter, particle sizer, laser generator and the laptop for real time monitoring. In the Compressed air source, the atomizer is connected to a source of compressed air at 3 bars. This allows the simulated spores (Polystyrene Polymers or PSP) suspended in an aqueous solution to be continuously atomized. The atomizer is a portable device, which employs pressurized air (up to 3 bars) to disperse PSP particles suspended in a solution. The dyer filter is an instrument to monitor the aerosol concentration within the wind tunnel in real time. The PSP particles fluoresce with an excitation value of 488nm (blue). In this manner, the instrument can analyse the aerosol and distinguish the particles produced by the atomizer from the other non-fluorescing particles in the air or inside the wind tunnel (e.g. dust, pollution). The laser generator is connected to the particle sizer, and produces an Ultra Violet laser beam to excite fluorescent particles. A laptop is connected via a serial cable to the particle sizer. This Allows for real time monitoring of aerosol data including particle concentration, fluorescence levels, and aerodynamic diameter of the particles.

80 grams sugar was dissolved with 4ml of dye UVITEX CF 200% (food colouring which fluoresces the sugar particles) and 1L of distilled water into the base of the smoke machine. The smoke machine is placed at the base of the wind tunnel airflow input duct and uses the same measuring equipment as for the first experiment.

After each experiment the samples (stored on the Melanex tape) were prepared onto glass slides and examined under a fluorescence microscope. The UVITEX CF dye has an excitation value of 350nm (DAPI) and the dissolved sugar particles are approximately 1micron in size.

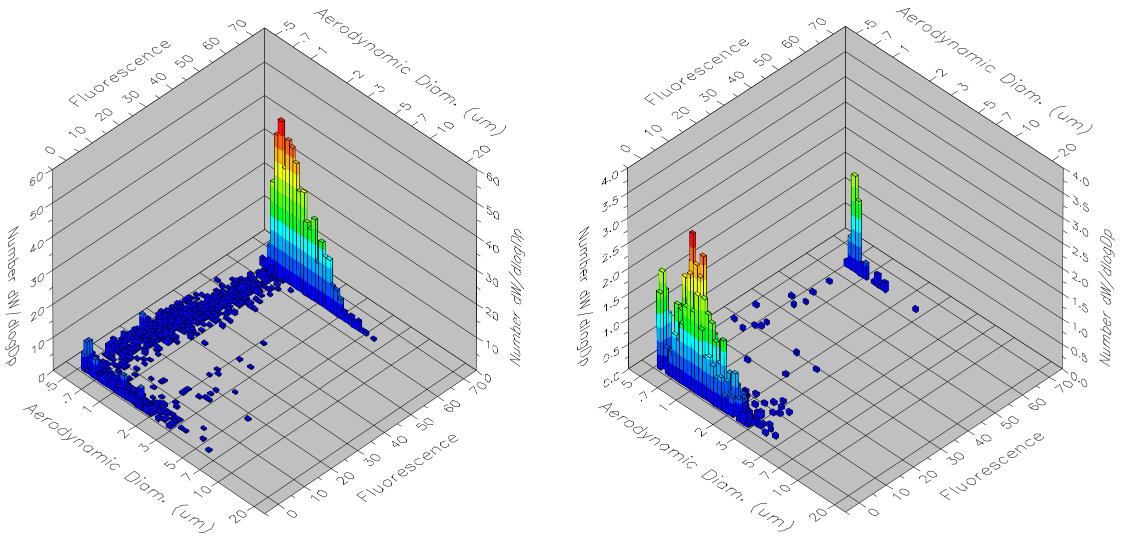
The polystyrene has an excitation value of 488nm (blue). The polystyrene particles are approximately 1micron in size.

4.2.2 Wind Tunnel Test Results and Discussion

The wind tunnel experiments highlighted several issues and difficulties to achieve the concentrations required for flight tests. It was found that the sugar had a high concentration (Figure 7.a) and the distribution in the wind tunnel was even. However, the polystyrene polymers ad a low concentration (Figure 8.b) and the distribution in the wind tunnel was not even (higher concentration in the centre). In these figures, the aerodynamic diameter (µm) reflects particle size and the fluorescence level provide the ability to separate the fluorescing simulated spores from background particles, which typically do not fluoresce. Additionally, the z axis represents the average particle concentration measured (particles/cm^3).

Samples were difficult to analyse under a fluorescent microscope as the particle sizes (~1micron) were smaller than those typically found for spores (generally 5-15microns). Larger spore samples could not be used, as larger particles (> 3microns) cannot be effectively dispersed using an atomizer ("Dispersing Microspheres in Air," 2003). Additionally sugar particles are limited in size to 1micron due to the nature of the smoke machine generator.

The polystyrene samples were very low in concentration (approximately 4-5 particles per cubic centimeter), and additionally due to the uneven distribution in the wind tunnel, they are not the suitable for capture in a wind tunnel simulations. The sugar particles could be released at a higher concentration (> 100 particles per cubic centimeter). However, they were difficult to analyse under a microscope as the vaseline used as the spore trap grease cannot be applied evenly. Vaseline is also excited at the same wavelength as UVITEX CF 200% and thus it is difficult to distinguish between the sugar and Vaseline solution.



a) b)

Figure 7. a) Sugar Concentration in wind tunnel b) PSP Concentration in wind tunnel. The polystyrene samples concentration was very low (4-5 particles per cubic meter) compared with the sugar concentration with levels above 40 particles per cubic meter. The colours represents the particle concentration (dark blue means low concentration, whilst red represent the highest concentration).

The one on the left red signifies a concentration of 50 particles and on the right red signifies about 2 particles concentration

4.3. Additional Wind Tunnel Experiments, methodology and results

Further wind tunnel testing was undertaken with a different wind tunnel in which Vaseline was replaced a recommended grease fv spores traps(cite Seven-Day Recording Volumetric Spore Trap). The spore trap grease was found to have a much lower auto-fluorescence level in comparison to Vaseline, and thus was more suitable for post analysis of these wind tunnel results.

Sugar particles (dissolved in distilled water and red food colouring) were dispersed using a smoke machine. The main difference between the first tests and the second wind tunnel testing was the use of spore trap grease (cite Seven-Day Recording Volumetric Spore Trap). Additionally, Polystyrene Polymers were not used for testing as it was concluded after the first wind tunnel tests, that the an ample concentration of particles in the airstream could only be produced using the dissolved sugar dispersed through the smoke machine.

The second wind tunnel tests were conducted at 20m/s (70 km/hr) as it is within the typical operational velocities of the UAS platform. The test was performed for 5 seconds and multiples of 5 seconds; a 5 second simulation represents a single pass over a 100m field. For a single pass (Figure 8a) in wind tunnel testing demonstrated that setting the spore trap fan voltage at 6V (isokinetic flow) resulted in the capture of a greater number of particles. However, the spread of the spores captured was greater. The result was consistent with testing for 10 and 30 seconds (Figure 8b).

White paper strips were used for visual verification of the spore capture process during the second wind tunnel testing. The spread (the cross sectional width of the spores captured on the tape) was measured for a range of simulation lengths (5, 10, 30 and 300 sec) and fan flow rates (0, 6 and 12V). The results are presented in Table 2.

Table 2 – Second Wind Tunnel Experiment Results

Velocity (m/s)	Sampling Time (sec)	Voltage (V)	Spread (mm)
20 (72 km/hr)	5	0	0.8
	5	6 (Isokinetic)	1.33
	5	12	0.8
20 (72 km/hr)	10	0	0.65
	10	6 (Isokinetic)	1.3
	10	12	0.7
20 (72 km/hr)	30	0	1.25
	30	6 (Isokinetic)	1.6
	30	12	1.25
20 (72 km/hr)	300	0	1.25
	300	6 (Isokinetic)	1.6
	300	12	1.25

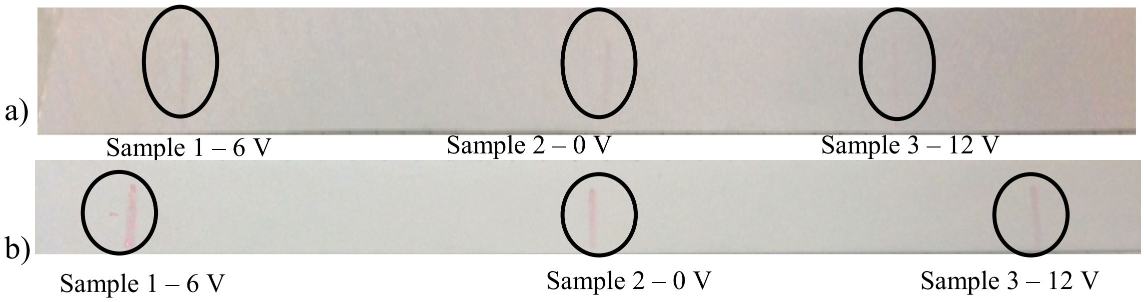


Figure 8. a) Wind Tunnel Test Results (Sampling Time 5s). In this picture it is possible to detect some of the sugar particles but others are not unclear such the ones using 2-0 volts to control the pumping rate (L/min) **b)** Wind Tunnel Test Results (Sampling Time 30s). This time particles are more clear due a longer time of exposure.

4.4. Summary of Wind Tunnel Testing

The Wind tunnel experiments demonstrated that the prototype spore trap sampling device could successfully capture particles in scenarios which simulated typical UAS operational velocities. However, in order to replicate these results, many variables such as particle concentration, airspeed, particle cross-sectional distribution, particle type and capture time is kept constant. During flight testing, many variables will not be controllable and may impact the spore traps ability to capture spores in different mission scenarios.

The following section presents the results of the flight tests conducted in order to verify the prototype sampling devices ability to capture spores in real world conditions.

5. Design and Simulation of Air Sampling

Depending on the specific application of the air sampling system, different missions can be designed and simulated. Following a general approach to the mission design, we can consider that in every problem of air sampling there is a defined zone to be kept under surveillance. The area of this zone can be different, depending on the application. The system architecture of our sampling system, allows different missions and applications. The limitations of the UAV platform (especially in terms of minimum turn radius) affect the shape of the flight plan and the waypoint positions. The optimal location of the waypoints for a certain zone depends primarily on the dimensions of the zone and secondarily on the weather conditions. The following sections describe different cases considered.

5.1. Monitoring a large or medium area

If the area to be monitored is medium to large, in relationship to the minimum turn radius capabilities of the UAV platform, a good structure for the waypoint position is reported in (Figure 10a, 10b). The minimum turn radius for the UAS is about 150 *m* in conditions of no wind. Obviously the situation could get worse depending on the wind direction and strenght.

The map used for the simulation is at ARCAA flight testing Burrandowan, QLD. The dimensions of the simulated field to monitor are 400 x 700 *m.* A field of 400 x 700 meters can be considered large for the UAS, because it can turn and remain inside the defined area. Hence, six active waypoints have been positioned near the border of the field, and three navigational waypoints have been positioned outside (we call active waypoints those inside the area to be monitored and navigational waypoints those outside, useful only to perform the mission). The number of samples over flied depends on the application in this case we try to maximise the number of passes and sampling points over the field. In this manner, the field can be monitored once with three paths, each separated from the other by a turn. The simulation was performed at the same target altitude. The shape is also determined by the most probable location of the infested plant(s) and wind plume that carries them. An example of application could be a sugar plantation, in which the presence of pollen and spores at a certain altitude has to be monitored and detected.

5.2. Monitoring a small area

If the area to be monitored is small, compared to the turn radius of the UAV, another flight plan has been developed. The position of the waypoint is reported in (Figure 10c,10d).

In this case, the dimensions of the simulated field are about 220 x 300 meters. If we want to perform an accurate sampling of the area, with six active waypoints and three different paths over the area, it is necessary to use more navigational waypoints. In this manner, the UAV can fly out of the field and cross it in the same direction (for example from west to east in Figure 10c,10d). The problem of this waypoint structure is that the UAV spends several time flying out of the field, overflying areas which are not of interest.

5.3. Monitoring different areas

One of the main advantages of having an air sampling system instead of a stationary system is related to the possibility to sample different areas in a single mission. If there are two large areas to be monitored; not too far in relationship to the range and the endurance of the UAV.

5.4. Sampling at different altitudes

The possibility of sampling the same area at different altitude is another interesting case to be considered. Assuming to have a large area to be sampled, if we want to monitor the spores particle concentration level or the presence of toxic gases at two different altitudes, a good waypoint structure could be that one reported in Figure 9.

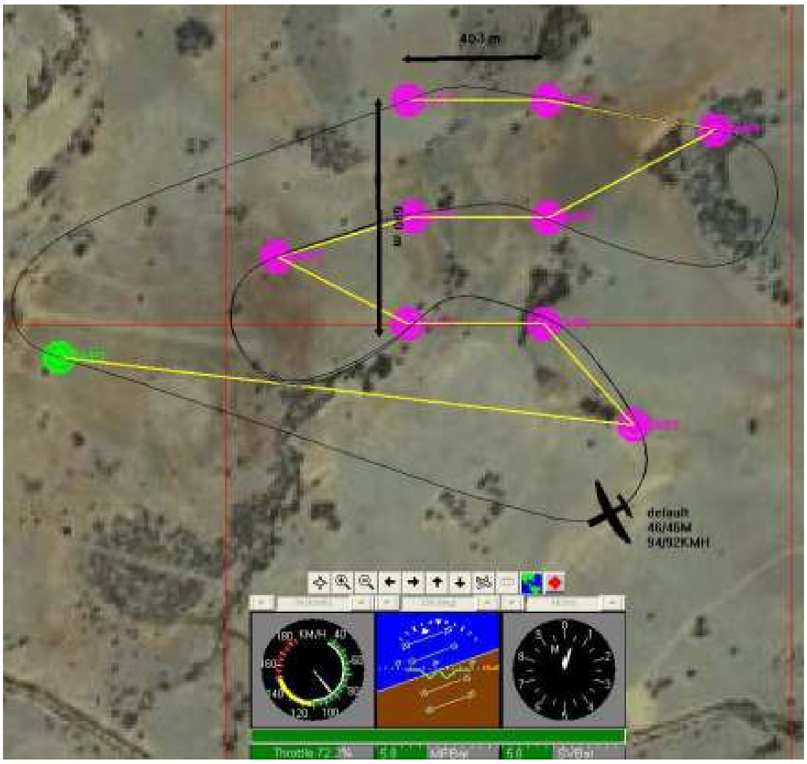


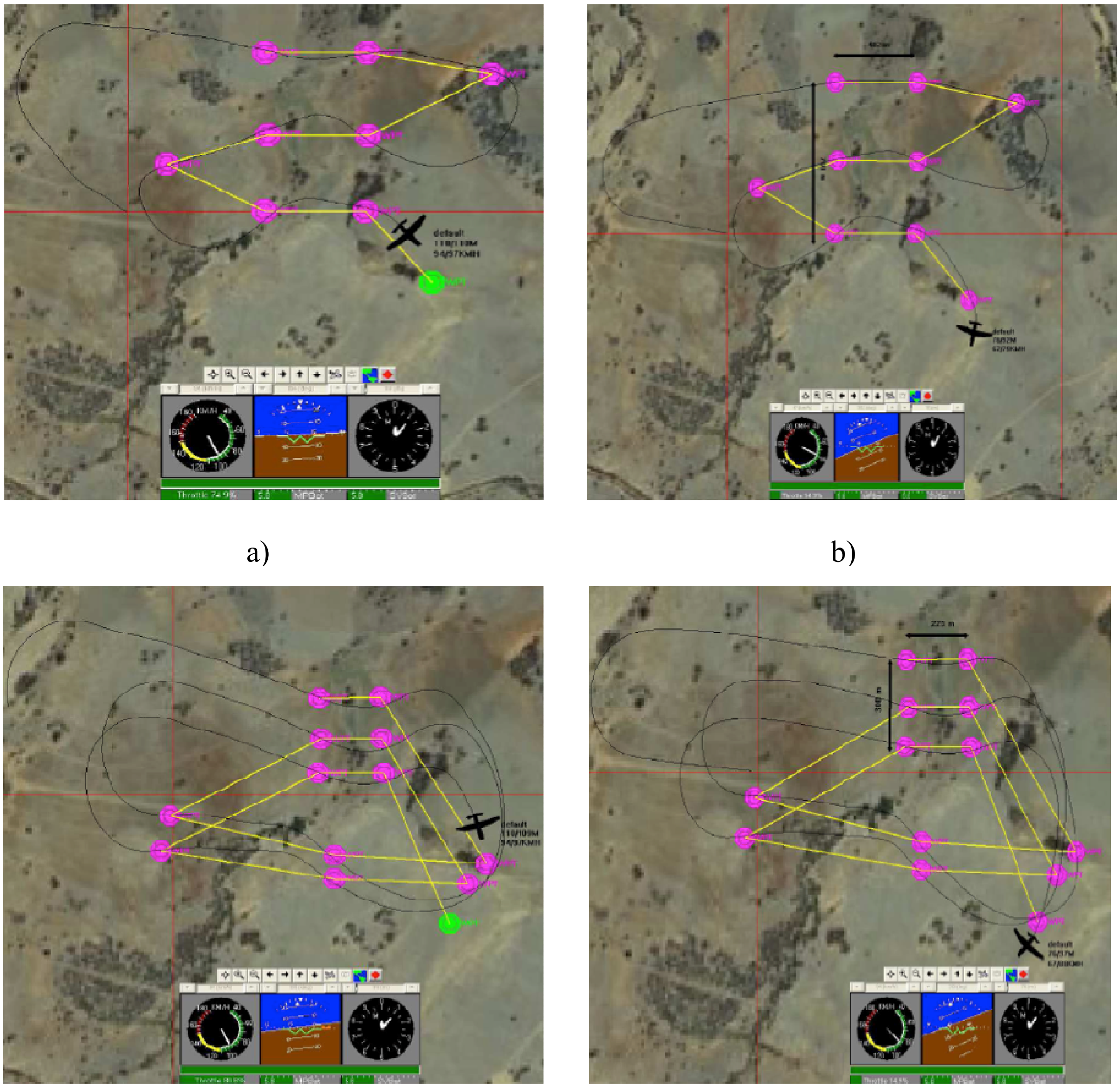
Figure 9. Sampling at different altitudes. The green waypoint in is a navigational waypoint which allows the UAV to descend and start again the sampling at a different altitude

In Figure 9 the altitude response is not very fast, it is attribute or the characteristics of to autopilot in which altitude is controlled by the throttle. The UAV needs a large distance to go from the first sampling altitude to the second one.

From these experiments we can observe that there are some overshoots and undershoots in the response and the length of the transitory phase of the response is about 40 sec. With the typical cruising speed of the UAS during the sampling mission is 20 *m/sec*, 800 meters will be necessary to descend from the altitude of 110 *m* to the altitude of 46 *m*. For this reason the green navigational waypoint in Figure 9, Figure 10a and Figure 10c is far from the area to be sampled.

5.5. Sampling in wind condition

The weather conditions, especially the wind, can affect the waypoint position and the flight plan to monitor a certain area. In order to analyse this influence we have simulated some scenarios with wind and no wind conditions. Figure 10 shows the effect of the wind on the flight of the UAS compared to the case with no wind.



a) b)

c) d)

Figure 10. In order to analyse the influence of the wind different UAS simulations were performed in two fields. An area of 400x700 meters for a),b) and an area of 200x 300 meters to analyse c),d). a) Wind from south at 11 knots b) No wind. c) Wind from south at 16 knots d) no wind

In this case, in spite of the wind, the mission can be performed. However, the trajectory of the UAV is less accurate and the flight is less stable. After the takeoff for example, the UAS cannot follow the right direction of the runway as in the case Figure 10 b. Figure 10c,d shows an example of the small field, in case of strong wind (16 knots from south) and no wind.

It is possible to observe that the wind in this case affects the capability of the UAS to perform the air-sampling mission. The trajectories are inaccurate, because the UAV try to fly against or with a strong cross wind. The small area (200 x 300 meters) to be monitored required more accurate trajectories for the actual waypoint structure. In practice knowing the wind speed and direction in advance would be needed to create a waypoint structure designed to compensate for wind.

6. Flight Testing

This section outlines the flight-testing methodology, the results obtained from the integration and flight-testing of the spore trap sensor onboard the UAS test bed.

6.1. Autonomous flight Stability and Spore Trap Functionality

The test involved integration of the spore trap with the QUT UAS. The spore trap height exceeded the payload bay size, thus an additional UAS canopy was purchased and modified to allow the spore trap to be fitted onboard. This flight test campaign was conducted on 13 November 2009 at Burrandowan (approximately 70km from Kingaroy, QLD, Australia).

Figure 11. Spore trap installation. The spore trap was fitted and secured onboard the UAS platform and the spore trap servo sensor driving the tape was integrated with the onboard autopilot system. The spore trap servo signal was supplied via a spare micropilot servo output. The PWM signal was isolated and a separate battery supplied the power to the servo. This ensured that if the spore trap servo jammed, power would still be available to onboard actuators.

The UAS was flown autonomously, and did not display any flight stability issues, which may have occurred due to the modifications necessary to the spare canopy to fit the spore trap in the platform. Furthermore, the servo was programmed to shift the tape by a predefined amount, while the tape shift occurred automatically when the platform reached a predefined waypoint. This was validated by the onboard autopilot and updated on the ground station Horizon GUI.

6.2. Capture of Fluorescent Sugar Particles during Autonomous Flight

Preliminary flight-testing allowed any minor integration issues to be resolved, and provided confidence that the prototype spore trap was within payload constraints to ensure safe autonomous operations whilst integrated onboard the UAS platform.

The spore trap capture flight was testing conducted in February 2010 at Burrandowan, Qld, Australia. The tests involved dispersion of fluorescent sugar particles into the atmosphere. Simulated particles were released with an electric blower into the atmosphere in a region simulating a small paddock (200 x 300 meters). The UAS was flown autonomously through the region and the spore trap was programmed to turn to a predefined sampling location (WP4 – WP5 in Figure 12). In order to avoid contaminating the test sample, once the UAS is outside the sampling region, the onboard system is programmed to the neutral position. The UAS performed five circuits and the region was sampled each time in the same sampling location thus aggregating the sampled results.

The sample presented in Figure 13 was captured during the autonomous flight at 100ft altitude. A wide focal microscope was used to analyse the sample. The fluorescing DAPI filter forced the UV sensitive dye that was applied to the sugar particles to fluoresce. The crystalline appearance differs from the rings present in the wind tunnel results. This can be attributed to the increase overall mission times before the samples were placed onto glass slides for analysis. The increased mission time allowed for the evaporation of the water in which the sugar was suspended within.

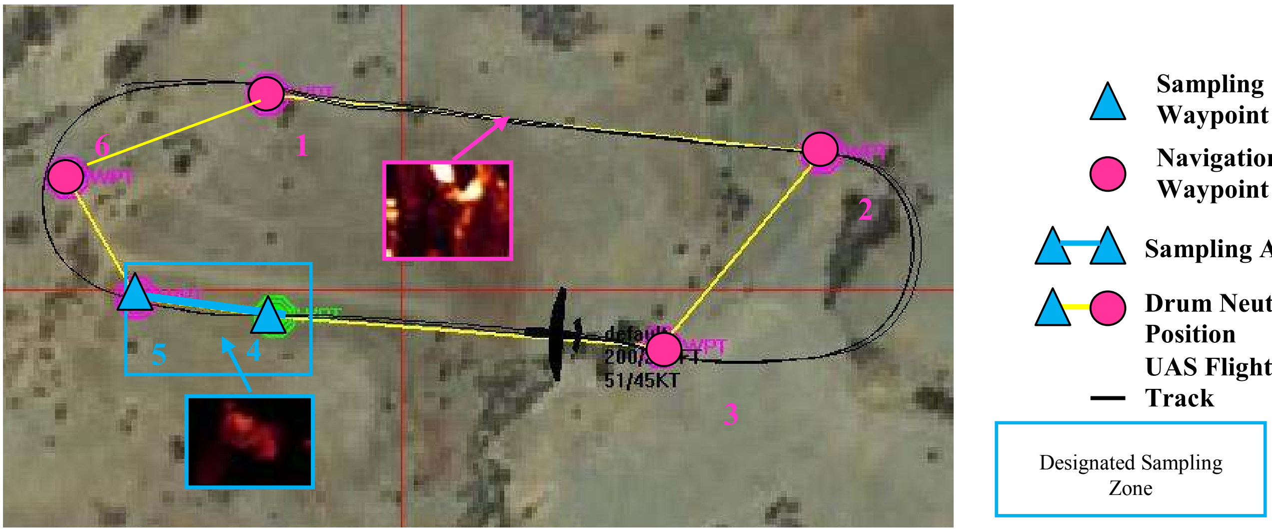


Figure 12. Geo-Referencing Captured Samples. It can be seen that the sample can be traced to the region indicated in the map overlayed on GPS coordinate data.

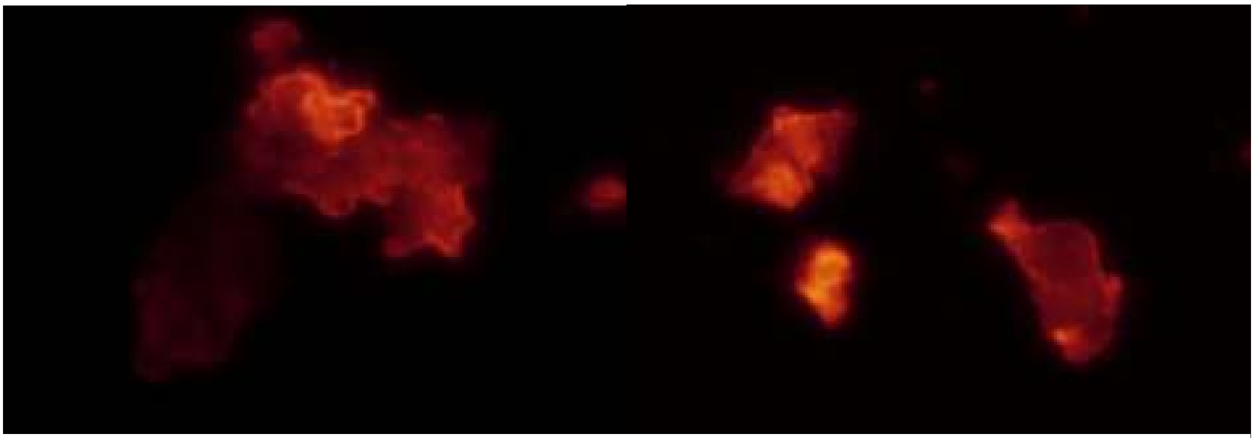


Figure 13. The flight test was conducted on 17 February 2010 at 11:30 am, at Burrandowan (approximately 70km from Kingaroy, QLD). These images are from the Microscope Analysis, showing the result of Autonomous Flight Test at sampling position 1 (when the spore trap is sampling at a desired position) the orange regions demonstrates the capture of fluorescent sugar particles. In total 70 particles were counted, considering a standard particle size of 30 µm. Figure 12 shows the location were these particles were taken. Based on the telemetry data the GPS location was -26.46456, 151.39702.

In order to quantify the amount of sugar particles in each region it was necessary to analyse the images from the microscope analysis (Figure 13). During the autonomous flight the UAS flew 5 times over the 200 meters region. The UAV spent 35 seconds (in total considering the 5 passes) to sample the region at 46 lt/min. In this region based on the image analysis from the microscope from Figure 13 the aggregated particle count was 70 particles. Therefore the estimate particle concentration was (46 lt/min x 0.58 min = 13300 cm^3, 70 particles / 13300 cm^3) 0.005 particles per cm^3, that is considering the standard sugar particle size of 30 µm.

6.3. Discussion of Flight Testing Results

Flight testing experiments conducted at Burrandowan, Qld demonstrated that the spore trap could be integrated onboard a UAS platform and successfully capturing and geo-locate particles during autonomous flight. Additionally, it was shown contamination could be avoided during the particle capture process through the inclusion of neutral locations on the tape which were activated while the UAS was outside a sampling region. The tape rotation mechanism was programmed to automatically shift the tape back to the sampling point once the UAS entered the sampling region again. Some practical implementation issues need to be considered. The following outcomes were achieved.

Integration of the flying spore with a greater overall weight of the UAS platform and lead to reduced endurance and operating velocities while satisfying stability and autonomous characterization of the UAS. The number of regions which can be surveyed in a typical mission will be limited by either, number of samples which can be collected the air sampling system or the UAS range and the sizes of the regions being surveyed. The current system's range is limited by the radio transmitters integrated onboard and can be deployed to paddocks at distances up to 2 Km from ground station.

All operations were conducted below 400 ft and required approval from the land owner, moreover it must be ensured that all operations are undertaken in unpopulated regions. Approval must also be gained from the Civilian Aviation Safety Authority (CASA) before any UAS operations can be undertaken at altitude greater than 400 ft or in populated regions.

Currently air sampling operations using the system are costly (typically $1000 AUD per day or greater). This is because a typical air sampling mission requires an autonomous UAS, ground station, UAS controller (e.g. take off/landing) and UAS operator (mission commander). The benefits (e.g. multi-region sampling, vertical profiling of pathogens) of aerial sampling outweigh the necessary platform and operational costs. Additionally aerial sampling allows for the surveying capability of remote regions, which are difficult/impossible to survey using ground based methods. The cost of operations will reduce over time and as UAV technology matures.

The optimal manoeuvre found in this research was to fly above tree canopy (for safety purposes) in a straight line defining a sampling and a navigation point. Further flight testing is required to determine the size and shape of the paddock that can be employed to determine an optimal set of manoeuvres which for the surveillance of a given region of interest. Optimality will be dependent on the human decision makers use of relevant criteria (e.g. maximise region sampled, minimise flight time/fuel, etc.) (Gonzalez, Lee, & Walker, 2010; Techy, et al., 2008).

A false alarm occurs when the air sampling system falsely detects the presence of pathogens in a particular region. It is important to understand probability of false alarm and how often will the system fail, and indicate that a diseased spore is present in a paddock when in fact it is not (possibly picked up en-route or on another paddock incorrectly). This relates to expenses associated with responding to the alarms created by the system. If we "lock down" are paddock due to this system developing an alarm then this impacts on the farmer and security enforcers. A system that is often producing false alarms will be quite useless to the relevant authorities and will quickly come out of service. This requires careful design and validation of a system to ensure that each unique sample is separated from previous samples to minimise contamination.

7. Conclusions and Future Work

This paper is an extension of existing work on the use of spores trap on aerial vehicles (Gottwald and Tedders, 1985) but allows to be controlled by and communications with autopilot subsystem. The paper described the development and testing the integration of a spore trap on an autonomous unmanned aerial system. We have developed a sampling system that has the ability to spatially monitor spores, and protocols to interpret their spatial distribution. These tools have the potential to enhance the ability to detect new incursions of fungal pathogens and to enable more accurate delimiting of distribution. Overall, the use of this technology allows early detection of EPP incursions in difficult areas. This approach has been demonstrated in this paper through wind tunnel experimentation, simulations and flight testings.

Initial Wind tunnel testing was performed and highlighted several issues such as dispersion of larger particles (> 3microns) and analysis of particles under fluorescent microscopes. Additional wind tunnel testing demonstrated that the prototype could successfully capture test particles (sugar) in a controlled environment which simulate typical flight conditions. The promising results obtained from wind tunnel experiments provided confidence to proceed with the flight testing phase.

Flight testing was conducted to verify the spore traps capability to capture spores in real world conditions. The spore trap was integrated with the test platform and onboard autopilot systems. Flight experiments demonstrated that the spore trap was able to successfully capture and geo-locate test particles (sugar) during autonomous missions. It was shown that sample contamination could be avoided through the inclusion of neutral locations on the tape. The tape rotation mechanism was programmed to automatically rotate the tape to the sampling location once the UAS entered the sampling region and shift the tape location to the neutral point once the UAS was outside the sampling region. Additionally all flight data was logged using the onboard autopilot data logger. A tape rotation algorithm was implemented to control the position of the drum to capture multiple samples without contamination. This allows for the geo-location of particles and for the characterisation of particle concentrations at discrete altitudes.

When a spore is trapped, the system is capable of indicating the geographical position of the sensor at the time the spore was detected. This allows the authorities to quarantine the site to prevent further spread of the disease. The accuracy will be dependent on the onboard position systems used, typically Global Positional System (GPS) for lateral position and altimeter for altitude.

The portable spore trap was compact enough to be integrated onboard the UAS platform. It was found that due to the higher operational velocities of the UAS, a smaller compact fan could be used, as opposed to the higher flow fans necessary for low altitude operations. Thus, it is still possible to further decrease the height and overall size/weight of the current prototype spore trap. A more compact version would potentially allow for integration with smaller UAS platforms.

Whilst wind tunnel and flight tests produced promising results, further testing is required for full verification of the spore traps capability to capture spores and pathogens. It is recommended that further flight testing be conducted via dispersed spores and over fields where known pathogens are present (e.g. Bundaberg, Qld).

Additionally, it is recommended that the spore trap be tested to identify the possibility of it being able to capture other particles types. This would allow for expansion of the use of the spore trap in other fields which can benefit aerial sampling.

It is important to consider several limitations in this research. The system proposed here it is limited to detect particles and its localization but it not able to track the movement of spores and therefore localize their source. Additional research it is needed in order to overcome this.

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References

Andersen, H.-E., McGaughey, R. J., & Reutebuch, S. E. (2005). Estimating forest canopy fuel parameters using LIDAR data. *Remote Sensing of Environment, 94*(4), 441-449.

Anderson, G. P., King, K. D., Cuttino, D. S., Whelan, J. P., Ligler, F. S., Mackrell, J. F., et al. (1999). Biological Agent Detection with the Use of An Airborne Biosensor. *Field Analytical Chemistry and Technology*(3), 307-314.

Aylor, D. E. (1990). The Role of Intermittent Wind in the Dispersal of Fungal Pathogens. *Annual Review of Phytopathology, 28*, 73-92.

Aylor, D. E. (1999). Biophysical scaling and the passive dispersal of fungus spores: relationship to integrated pest management strategies. *Agricultural and Forest Meteorology, 97*, 275–292.

Aylor, D. E., & Boehm, M. T. (2006). Quantifying Aerial Concentrations of Maize Pollen in the Atmospheric Surface Layer Using Remote-Piloted Airplanes and Lagrangian Stochastic Modeling. *Journal of Applied Meteorology and Climatology, 45*, 1003-1015.

Berni, J., Zarco-Tejada, P. J., Suarez, L., & Fereres, E. (2009). Thermal and Narrowband Multispectral Remote Sensing for Vegetation Monitoring From an Unmanned Aerial Vehicle. *Geoscience and Remote Sensing, IEEE Transactions on, 47*(3), 722-738.

Cioffarelli, A., & Natale, M. T. (2000). *Guide to the catacombs of Rome and its surroundings* (English ed.). Rome: Bonsignori.

Cleugh, H. A., Leuning, R., Mu, Q., & Running, S. W. (2007). Regional evaporation estimates from flux tower and MODIS satellite data. *Remote Sensing of Environment, 106*(3), 285-304.

Cole, D. T., Sukkarieh, S., & Göktoğan, A. H. (2006). System development and demonstration of a UAV control architecture for information gathering missions. *Journal of Field Robotics, 23*(6-7), 417-440.

Corrigan, C. E., Roberts, G. C., Ramana, M. V., Kim, D., & Ramanathan, V. (2008). Capturing Vertical Profiles of Aerosols and Black Carbon over the Indian Ocean using Autonomous Unmanned Aerial Vehicles. *Atmospheric Chemistry and Physics*(8), 737-747.

Cox, C. S., & Wathes, C. M. (Eds.). (1995). *Bioaerosols Handbook* Lewis Publishers.

CRC30032: Flying Spore Traps. Retrieved 2011 May, Available from: http://www.crcplantbiosecurity.com.au/program/surveillance/project/crc30032.

Dingus, B. R. (2008). *Development of an Autonomous Unmanned Aerial Vehicle for Aerobiological Sampling.* Virginia Polytechnic Institute, Blacksburg.

Dispersing Microspheres in Air. (2003). Fremont: Thermo Scientific.

Emili, E., Popp, C., Petitta, M., Riffler, M., Wunderle, S., & Zebisch, M. (2010). PM10 remote sensing from geostationary SEVIRI and polar-orbiting MODIS sensors over the complex terrain of the European Alpine region. *Remote Sensing of Environment, In Press, Corrected Proof.*

Flamingo Umanned Aerial Vehicle. (2009). Retrieved July, 2009, from http://www.silvertoneuav.com/

Gonzalez, L. F., Lee, D. S., & Walker, R. A. (2010). *Mission Path Planning (MPP) for an*

Unmanned Aerial System (UAS) fitted with an air sampling device. Paper presented at the Global Bio-security 2010 Conference.

Goodrich, M. A., Morse, B. S., Gerhardt, D., Cooper, J. L., Quigley, M., Adams, J. A., et al. (2008). Supporting wilderness search and rescue using a camera-equipped mini UAV: Research Articles. *Journal of Field Robotics, 25*(1-2), 89-110.

Gottwald, T. R. and W. L. Tedders (1985). "A spore and pollen trap for use on aerial remotely piloted vehicles." Phytopathology 75(7): 801-807.

Guoqing, Z., & Deyan, Z. (2007, 23-28 July 2007). *Civil UAV system for earth observation.* Paper presented at the Geoscience and Remote Sensing Symposium, 2007. IGARSS 2007. IEEE International.

Ingold, C. T. (1939). *Spore discharge in land plants.* . Oxford: The Clarendon Press.

Karim, S., Heinze, C., & Dunn, S. (2004, 14-17 Dec. 2004). *Agent-based mission management for a UAV.* Paper presented at the Intelligent Sensors, Sensor Networks and Information Processing Conference, 2004. Proceedings of the 2004.

Kaupp, T., Douillard, B., Ramos, F., Makarenko, A., & Upcroft, B. (2007). Shared environment representation for a human-robot team performing information fusion. *Journal of Field Robotics, 24*(11-12), 911-942.

Ligler, F. S., Anderson, G. P., Davidson, P. T., Foch, R. J., Ives, J. T., King, K. D., et al. (1998). Remote Sensing Using an Airborne Biosensor. *Environmental Science & Technology, 32*(16), 2461-2466.

Ligler, F., et al. (1993) , Remote Sensing Using an Airborne Biosensor, *Journal of Chromatography A, Volume 646, Issue 1, Pages 45-52*

MicroPilot 2128g. (2009). Retrieved July, 2009, from http://www.micropilot.com/products-mp2128g.htm

Murphy, R. R., Steimle, E., Griffin, C., Cullins, C., Hall, M., & Pratt, K. (2008). Cooperative use of unmanned sea surface and micro aerial vehicles at Hurricane Wilma. *Journal of Field Robotics, 25*(3), 164-180.

Patenaude, G., Hill, R. A., Milne, R., Gaveau, D. L. A., Briggs, B. B. J., & Dawson, T. P. (2004). Quantifying forest above ground carbon content using LiDAR remote sensing. *Remote Sensing of Environment, 93*(3), 368-380.

Peräjärvi, K., Lehtinen, J., Pöllänen, R., & Toivonen, H. (2008). Design of an air sampler for a small unmanned aerial vehicle. *Radiation Protection Dosimetry, 132*(3), 328-333.

Plant Biosecurity, 2011. Retrieved May 2011, from: http://www.crcplantbiosecurity.com.au/about-us/plant-biosecurity

Rosette, J. A. B., North, P. R. J., Su\, J. C., (2008). Vegetation height estimates for a mixed temperate forest using satellite laser altimetry. *International Journal of Remote Sensing., 29*(5), 1475-1493.

Running, S. W., Baldocchi, D. D., Turner, D. P., Gower, S. T., Bakwin, P. S., & Hibbard, K. A. (1999). A Global Terrestrial Monitoring Network Integrating Tower Fluxes, Flask Sampling, Ecosystem Modeling and EOS Satellite Data. *Remote Sensing of Environment, 70*(1), 108-127.

Sanders, C., Rodriguez, M., Greenbaum, E., Stand-off tissue-based biosensors for the detection of chemical warfare agents using photosynthetic fluorescence induction (2001). *Biosensors and Bioelectronics, Volume 16, Issues 7-8, Pages 439-446.*

Schmale, D. G., Dingus, B. R., & Reinholtz, C. (2008). Development and application of an autonomous unmanned aerial vehicle for precise aerobiological sampling above agricultural fields. *Journal of Field Robotics*, 133-147.

Schwartz, M. T., & Billoski, T. V. (1990). Greenhouse hypothesis: effect on dinosaur extinction. In B. T. Jones & N. V. Lovecraft (Eds.), *Extinction* (pp. 175-189). New York: Barnes and Ellis.

Techy, L., Schmale, D. G., & Woolsey, C. A. (2010). Coordinated Aerobiological Sampling of a Plant Pathogen in the Lower Atmosphere Using Two Autonomous Unmanned Aerial Vehicles. *Journal of Field Robotics, 27*(3), 335–343.

Techy, L., Woolsey, C. A., & G., S. D. (2008 Dec. 9-11,). *Path Planning for Efficient UAV Coordination in Aerobiological Sampling Missions.* Paper presented at the 47th IEEE Conference on Decision and Control, Cancun, Mexico.

Volumetric Spore Trap. (2009). Retrieved July, 2009, from http://www.burkard.co.uk/7dayst.htm

Wagner, J., & Leith, D. (2001). Passive Aerosol Sampler. Part II: Wind Tunnel Experiments. *Aerosol Science and Technology, 34*(2), 193 — 201.

Watson, D. (2007). *The Economic Impact of Sugarcane Smut on the Queensland Sugarcane Industry*.

Zeller, L. (2007). *Development of indexing spore trap for use with remotely controlled aircraft.* Paper presented at the CRC National Plant Biosecurity Science Exchange.

Zhang R., Zhang, Z., Liu, G., et al. (1993), High-performance liquid chromatographic determination of neutral and amino monosaccharides by ultraviolet and fluorescence detection of sugar 9-fluoroenylmethoxycarbonyl hydrazones and 9-fluoroenylmethoxycarbonyl amino sugars at picomole and sub-picomole levels, *Journal of Chromatography A*, Volume 646, Issue 1, Pages 45-52

Zhou, G., Ambrosia, V., Gasiewski, A. J., & Bland, G. (2009). Unmanned Airborne Vehicle (UAV) Sensing Systems for Earth Observations. *IEEE Transactions on Geoscience and Remote Sensing, 47*(Special Issue).