Remote-controlled (RC) unmanned aerial vehicles (UAVs) have been used to study the movement of agricultural threat agents (e.g., plant and animal pathogens, invasive weeds, and exotic insects) above crop fields, but these RC UAVs are operated entirely by a ground-based pilot and often demonstrate large fluctuations in sampling height, sampling pattern, and sampling speed. In this paper, we describe the development and application of an autonomous UAV for precise aerobiological sampling tens to hundreds of meters above agricultural fields. We equipped a Senior Telemaster UAV with four aerobiological sampling devices and a MicroPilot-based autonomous system, and we conducted 25 sampling flights for potential agricultural threat agents at Virginia Tech’s Kentland Farm. To determine the most appropriate sampling path for aerobiological sampling above crop fields with an autonomous UAV, we explored five different sampling patterns, including multiple global positioning system (GPS) waypoints plotted over a variety of spatial scales. An orbital sampling pattern around a single GPS waypoint exhibited high positional accuracy and produced altitude standard deviations ranging from 1.6 to 2.8 m.
1. INTRODUCTION

Improved technologies are needed to anticipate, prevent, prepare for, and respond to the introduction of agricultural threat agents (e.g., plant and animal pathogens, invasive weeds, and exotic insects) into crop fields (Madden & Wheelis, 2003; Strange & Scott, 2005). Many of these threat agents have the potential to be transported over great distances in the atmosphere (Aylor, 2003; Isard & Gage, 2001), threatening agriculture in the United States from both inside and outside the borders of the country. The ability to detect, monitor, and forecast the movement of agricultural threat agents in the atmosphere is essential for establishing effective quarantine measures, preventing the spread of disease, and mitigating potentially damaging events targeted at our nation’s agriculture and food supply (Aylor, 1986, 1999; Strange & Scott, 2005).

The long-distance transport of many agricultural threat agents takes place primarily in the planetary boundary layer (PBL) of the atmosphere—the layer of the atmosphere that extends from approximately 50 m to 1 km above the surface of the earth (Isard & Gage, 2001; Maldonado-Ramirez, Schmale, Shields, & Bergstrom, 2005). Agents transported through the PBL can move over kilometer distances in a matter of minutes (Isard & Gage, 2001). Little is known about the aerobiological processes that govern the movement of agricultural threat agents in the PBL, and new tools for studying their movement in the atmosphere need to be developed and implemented.

Within the past decade, remote controlled (RC) unmanned aerial vehicles (UAVs) have been used to study the movement of insects, pollen, plant pathogens, and seeds in the PBL. Shields and Testa (1999) used RC UAVs to study the long-distance movement and migratory behavior of the potato leafhopper insect Empoasca fabae. Aylor, Boehm, and Shields (2006) used RC UAVs to monitor and model the long-distance movement of corn pollen in the lower atmosphere. Maldonado-Ramirez et al. (2005) used RC UAVs to collect seeds of horseweed, Conyza canadensis, up to 150 m above agricultural fields. In these studies, RC UAVs were equipped with aerobiological sampling devices that were opened and closed by remote control from the ground once the UAV was aloft. The RC UAVs traveled at speeds up to 100 km/h and had the capacity to sample around 10,000 liters of air per min using a 100-mm-diameter sampling surface (Maldonado-Ramirez et al., 2005). Each RC UAV carried four sampling surfaces for a total sampling capacity of approximately 40,000 liters of air per min—orders of magnitude greater than traditional stationary sampling devices (Maldonado-Ramirez et al., 2005). UAVs provide the high-volume sampling capacity required to study the movement of agricultural threat agents in the lower atmosphere.

There are a number of challenges in using RC UAVs to collect aerobiological samples, including maintaining a precise altitude, following a specific sampling pattern, and sustaining a consistent sampling speed. Small variations in altitude, pattern, and/or speed may significantly impact measurements and model calculations of atmospheric transport. In their aerobiological sampling of horseweed with RC UAVs, Shields et al. (2006) experienced altitude standard deviations ranging from 9 to 19 m above and below their target sampling altitude and sampling speed standard deviations ranging from 6 to 13 km/h above or below their target sampling speed. Maldonado-Ramirez et al. (2005) experienced sampling pattern deviations on the scale of fields. Because RC UAVs are operated entirely by a ground-based pilot, they are also limited by line-of-sight operation and pilot fatigue.

Recent advances in autonomous systems technologies have produced a new generation of small, compact autopilots for UAVs, including MicroPilot (MicroPilot, Inc., Stony Mountain, Manitoba, Canada) and Piccolo (Cloud Cap Technology, Inc., Hood River, Oregon). Autopilots such as these have been integrated into a number of UAV platforms for various reconnaissance and surveillance missions, but autonomous systems technologies have only recently been used for civilian applications (Ollero & Merino, 2004). Here, we describe the development and application of an autonomous UAV.
to improve the precision and accuracy of aerobiological sampling above agricultural fields. The specific objectives of this study were to (1) develop a practical autonomous UAV platform for aerobiological sampling tens to hundreds of meters above agricultural fields, (2) monitor the ability of the autonomous UAV to maintain a precise sampling altitude, sampling pattern, and sampling speed during aerobiological sampling, and (3) determine the most appropriate sampling pattern for aerobiological sampling above agricultural fields with an autonomous UAV. An abstract of a portion of this work has been published (Dingus, Schmale, & Reinholtz, 2007). Autonomous UAVs have the potential to extend the range of aerobiological sampling, improve positional accuracy of sampling paths, and enable coordinated flight with multiple UAVs sampling at different altitudes.

2. UAV PLATFORM

The Senior Telemaster (ST) model airplane (Hobby Lobby International, Inc., Brentwood, Tennessee) was used as our aerobiological sampling platform (Figure 1). The ST had a wingspan of 2.4 m with 1,330 in.² of wing area and 320 in.² of rear stabilizer area. The ST was equipped with an oversized 1.2-in.³ engine (O.S. Engines, Champaign, Illinois) that produced 3.1 horsepower (hp) at 9,000 rpm (Figure 1) and a Master Airscrew 15 × 8 in. K-Series propeller (Windsor Propeller Company, Rancho Cordova, California). The factory engine mounts were trimmed to accommodate the engine, and the servo tray was modified to accommodate the autonomous system. The stock servo tray was cut in half to allow additional space inside the fuselage. Half of the servo tray was used to mount the rudder and elevator servos. The throttle servo was mounted in the front of the plane just behind the firewall to allow a pushrod to pass through the original hole in the firewall. Custom servo mounts were glued in place and a micro servo (Futaba S3101; Futaba, Champaign, Illinois) was installed to operate the throttle. The second half of the servo tray was modified to house the batteries. Mounts for the wing struts were installed on the fuselage using a removable clevis-hitch pin (881075/881096; Hillman, Cincinnati, Ohio) and a custom aluminum bracket mounted to the bottom of the fuselage. The wing struts were attached to the wings with standard control surface hinges (GPMQ3971; Great Planes, Champaign, Illinois), providing a secure joint between the strut and the wing. On the other end of the struts, a hole was drilled to accept the clevis. Washers were attached with epoxy around the holes to reinforce the connection.

2.1. Flight Controller

The MicroPilot MP2028g system (MicroPilot, Inc., Stony Mountain, Manitoba, Canada) was used as our autonomous flight controller. The MicroPilot MP2028g system is lightweight (28 g), has good functionality, and is relatively affordable. The system permits a UAV to navigate global positioning system (GPS) waypoints through a desired sampling area while providing the ground-based pilot with real-time dynamic control of flight characteristics. The MicroPilot MP2028g system was a printed circuit board equipped with 3-axis gyroscopes and accelerometers. These components provided inertial measurements to allow control of the roll, pitch, and yaw of the UAV. A GPS unit attached to the board received satellite signals through the attached antenna, a static pressure sensor allowed the autopilot to measure relative altitude, and a pitot tube pressure sensor monitored the airspeed of the UAV. A compass module (MP-COMP; MicroPilot, Inc.) was added to the MicroPilot to determine the true heading of the UAV. The combination of GPS heading, compass heading, GPS speed, and airspeed allowed the autopilot to calculate wind velocity and direction, ultimately...
resulting in a more precise sampling path. An ultrasonic above-ground-level (AGL) sensor (MP-AGL; MicroPilot, Inc.) was added to permit autonomous takeoff and landing. This sensor used an ultrasonic transducer mounted on the bottom side of the fuselage to calculate distances to ground level at altitudes below 5 m. The sensor was connected to the autopilot via a shielded coaxial cable. An analog-to-digital converter (ADC) (MP-ADC; MicroPilot, Inc.) was added to measure battery voltages that were used to power other components of the system. All of the control surfaces on the UAV were controlled by the autopilot. The signal for the servos passed through a servo board, allowing the power supply to the servo to be independent of the power supply to the MicroPilot. The UAV was controlled manually via a 72-MHz RC transmitter. The receiver (FUTJ7122; Futaba) on the UAV had its signal passed through the autopilot board. Control was transferred to and from the autopilot by a switch on the RC transmitter (FUTJ7122; Futaba). When in manual mode, the signal was passed through the autopilot to the servo board and the pilot on the ground had full control of the UAV.

An electronics box was used to house all of the MicroPilot components (Figure 2). The autopilot and the radio modem were powered by separate 11.1-V lithium-ion battery packs with 2,200-mAh capacity (L18650-2200-3; Tenergy Corporation, Sunnyvale, California). The UAV control surface servos used a 4.8-V nickel–cadmium battery pack with 600-mAh capacity (NR-4J; Futaba), and the aerobiological sampling devices used a 4.8-V nickel metal hydride battery pack with 2,000-mAh capacity (HCAM6320; Hobbico, Champaign, Illinois). Separate batteries were used, because the servos for the aerobiological sampling devices have the potential to draw very high amounts of power when they are opened and closed during flight.

2.2. Aerobiological Sampling Devices

Aerobiological sampling devices were designed with two large-sail servos (HS-765HB; Hitec, Poway, California) mounted in a wooden frame and attached to the bottom of each wing. Each servo operated an individual arm containing a 100-mm petri dish lid. During aerobiological sampling, the petri dish bottom containing a desired aerobiological culture medium was taped into the lid on the servo arm. Another lid was permanently attached to a piece of plywood mounted between the two servos. The sampling devices were closed during takeoff and landing and were opened when the UAV was at the desired sampling altitude. The sampling devices remained open for the entire duration of the 15-min aerobiological sampling flight. In previous work by Maldonado-Ramirez et al. (2005), the aerobiological sampling devices were mounted under the wing near the center of the wing chord and had servo arms that were approximately 8 in. long. The major problem encountered with this design was the poor dynamic stability of the UAV when the sampling devices were opened or closed (Wang, Patel, Woolsey, Hovakimyan, & Schmale, 2007). When the sampling devices were opened to begin sampling, the plane would suddenly begin to pitch nose down because the devices introduced a large amount of drag below the aerodynamic center of the UAV. To remedy this problem, the sampling devices were redesigned to allow the petri dishes to open on the leading edge of the wing (Figure 3). This change essentially eliminated the pitching of the UAV when the sampling devices were opened. The effective lifting force of the wing was reduced slightly, because there was now turbulent air flowing over the airfoil directly behind the sampling devices. On larger planes, this reduced lifting ability is typically not an issue because the UAV is not carrying its maximum payload.

Figure 2. Flight controller housed in an electronics box containing the following components: (a) extension for the pitot tube, (b) RC receiver, (c) MicroPilot MP2028g, (d) compass, (e) servo expansion board, (f) GPS connection, and (g) wires for power and data.
The sampling devices were mounted to the wings of the UAV using industrial-strength Velcro. This mounting method allowed the sampler to detach upon a very hard or crash landing, which helped to prevent the sampler from damaging the wing. Power and signal was provided to the sampler servos by 36-in. servo extensions (HCAM2726; Hobbico) routed inside the wing. Servo extensions were installed inside the wing with the plug flush with the bottom of the wing. The extensions were glued in place vertically to ensure that, if the sampling device was to become detached from the wing, the servo wire would be pulled out by the weight of the sampler without ripping the extension through the wing. The four sampling servos were controlled via a single RC channel that was routed through a servo synchronizer (MSA-10; Futaba) that allowed the samplers to have a power source independent from the rest of the UAV. Each servo could be adjusted independently to ensure that it was moving in the correct direction and stopping at the appropriate places in both the opened and closed positions.

Two types of aerobiological culture media were used in this research. The first was a *Fusarium*-selective medium (FSM) that allows only fungi in the genus *Fusarium* to grow (Maldonado-Ramirez et al., 2005). The second is potato dextrose agar (PDA), a general medium for the cultivation of many different prokaryotic and eukaryotic microbes.

3. GROUND CONTROL STATION

The ground control station (GCS) consisted of a Compaq laptop computer running MicroPilot Horizon software (Figure 4). The UAV communicated with the GCS via a 900-MHz radio modem, allowing real-time monitoring and control of nearly all aspects of flight. Flight files containing GPS waypoints could be modified and uploaded during flight, and the Horizon software could be programmed to read flight parameters from the ADC and display the information on the laptop in real time. State values that were programmed to show on the graphical user interface...
(GUI) were altitude, airspeed, GPS speed, and compass heading.

Proportional, integral, and derivative (PID) control loop gains in MicroPilot were used to monitor and control flight performance and were adjusted using the GCS. The PID loops consisted of (1) aileron from desired roll, (2) elevator from desired pitch, (3) rudder from Y-accelerometer, (4) rudder from heading, (5) throttle from speed, (6) throttle from glide slope, (7) pitch from altitude, (8) pitch from AGL altitude, (9) pitch from airspeed, (10) roll from heading, and (11) heading from cross track. All loops that operate control surfaces on the UA V were updated at a rate of 30 Hz, which includes loops (1), (2), (3), and (4). All other control loops were updated at 5 Hz. The results from the inner loops (7, 8, 9, 10, and 11) were used as inputs to the outer control loops that control the actual control surfaces of the UA V. The gains were tuned to achieve the desired level of accuracy in flight.

A series of preliminary flights were conducted with the UA V to optimize flight characteristics and adjust gains. During these initial autonomous flights, the UA V was flown for 15 min under the direct control of the autopilot. We made small changes to the gains on the ground before each of the flights, flew for another 15 min, and tuned the gains on the ground before the next sampling flight. Gains were adjusted following a series of control loops recommended by MicroPilot. Maintaining an accurate altitude was considered to be the most important aspect of flight performance and aerobiological sampling; therefore most of the time tuning the gains was spent trying to reduce the variations in altitude during sampling. The positional accuracy of the sampling patterns was visually inspected within flights on a per-loop basis and also compared between different flights following the same pattern. After 32 sampling flights, we arrived at an appropriate set of gains. We used this set of optimized gains for the following 25 sampling flights, which are the focus of the data that are presented here. No additional changes or adjustments to the autopilot were made during any of the following 25 sampling flights.

4. PATTERNS FOR SAMPLING FLIGHTS

To determine the most appropriate sampling path for aerobiological sampling above agricultural fields with an autonomous UA V, we explored five different sampling patterns, including multiple GPS waypoints plotted over a variety of spatial scales. The size and shape of the sampling pattern was designed specifically for sampling above typical agricultural fields. All of the patterns were developed to keep the UA V within the line of sight of the pilot, in the event that the pilot needed to take control of the aircraft via RC during an emergency. The UA V was programmed to maintain a target altitude while flying the following five patterns at an airspeed of 60 km/h: (1) single GPS waypoint (referred to hereafter as point), (2) two GPS waypoints separated by 325 m (referred to hereafter as line), (3) three GPS waypoints arranged in an equilateral triangle with each leg measuring 325 m (referred to hereafter as triangle), (4) four GPS waypoints arranged in a rectangle measuring $325 \times 150$ m (referred to hereafter as rectangle), and (5) four GPS waypoints arranged in a rectangle measuring $325 \times 150$ m, but with the navigation order changed to create a figure-8 pattern (referred to hereafter as figure-8). The figure-8 pattern utilized a different navigation command to navigate the longer legs of the pattern. The MicroPilot fromto command was used to force the autopilot to try to fly directly on the line connecting the waypoints instead of just flying toward the next waypoint. Flight data were downloaded from the autopilot after each flight and were imported into MATLAB for calculations and plotting.

5. RESULTS

We conducted a total of 25 autonomous sampling flights above agricultural fields at Virginia Tech’s Kentland Farm (Table 1). Five flights were conducted for each of the five sampling patterns, and flight time during sampling was approximately 15 min. Twenty-two of the flights were conducted at a target altitude of 100 m, and one flight each was conducted at target altitudes of 60, 200, and 300 m, respectively. Sampling flights were conducted between the hours of 9:45 am and 5:15 pm from 11 November 2006 to 25 March 2007. Meteorological conditions encountered during sampling ranged from clear and calm to cloudy and windy. Mean airspeed recorded during sampling ranged from 59.9 to 61.8 km/h.

5.1. Accuracy of Sampling Altitude

The point pattern produced altitude standard deviations ranging from 1.6 to 2.8 m, with a mean altitude standard deviation across all five flights of 2.0 m. Figure 5 demonstrates the accuracy of the sampling

<table>
<thead>
<tr>
<th>Flight</th>
<th>Date</th>
<th>Time</th>
<th>Media(^a)</th>
<th>Altitude(^b) (m)</th>
<th>Interval(^c) (s)</th>
<th>Airspeed(^d) (km/h)</th>
<th>Pattern</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>12:05 pm</td>
<td>FSM</td>
<td>99.9 ± 3.9</td>
<td>902.2</td>
<td>60.0</td>
<td>Figure-8</td>
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<tr>
<td>2</td>
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<td>99.9 ± 1.9</td>
<td>903.4</td>
<td>60.0</td>
<td>Point</td>
</tr>
<tr>
<td>3</td>
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<td>FSM</td>
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<td>903.2</td>
<td>60.0</td>
<td>Point</td>
</tr>
<tr>
<td>4</td>
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<td>11:45 am</td>
<td>FSM</td>
<td>99.8 ± 2.2</td>
<td>903.4</td>
<td>60.1</td>
<td>Rectangle</td>
</tr>
<tr>
<td>5</td>
<td>25-Nov-06</td>
<td>12:15 pm</td>
<td>FSM</td>
<td>99.9 ± 2.5</td>
<td>903.4</td>
<td>60.0</td>
<td>Triangle</td>
</tr>
<tr>
<td>6</td>
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<td>12:45 pm</td>
<td>FSM</td>
<td>99.9 ± 2.5</td>
<td>903.4</td>
<td>60.0</td>
<td>Triangle</td>
</tr>
<tr>
<td>7</td>
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<td>1:30 pm</td>
<td>FSM</td>
<td>99.9 ± 2.8</td>
<td>903.2</td>
<td>60.1</td>
<td>Triangle</td>
</tr>
<tr>
<td>8</td>
<td>25-Nov-06</td>
<td>2:00 pm</td>
<td>PDA</td>
<td>60.0 ± 1.8</td>
<td>903.4</td>
<td>60.0</td>
<td>Point</td>
</tr>
<tr>
<td>9</td>
<td>25-Nov-06</td>
<td>2:30 pm</td>
<td>PDA</td>
<td>199.9 ± 2.0</td>
<td>903.4</td>
<td>60.0</td>
<td>Point</td>
</tr>
<tr>
<td>10</td>
<td>25-Nov-06</td>
<td>3:00 pm</td>
<td>FSM</td>
<td>999.9 ± 2.8</td>
<td>602.0</td>
<td>59.9</td>
<td>Point</td>
</tr>
<tr>
<td>11</td>
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<td>3:30 pm</td>
<td>FSM</td>
<td>100.0 ± 6.1</td>
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<td>Line</td>
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<td>60.0</td>
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<td>100.0 ± 1.6</td>
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<td>Rectangle</td>
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<td>Line</td>
</tr>
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<td>Line</td>
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<td>95.2 ± 14.4</td>
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<td>Line</td>
</tr>
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<td>9:45 am</td>
<td>FSM</td>
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<tr>
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<td>10:15 am</td>
<td>PDA</td>
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<td>FSM</td>
<td>100.0 ± 5.0</td>
<td>887.4</td>
<td>60.0</td>
<td>Triangle</td>
</tr>
</tbody>
</table>

\(^a\)FSM, Fusarium-selective medium; PDA, potato dextrose agar.
\(^b\)Mean altitude recorded during flight ± standard deviation.
\(^c\)Total sampling interval.
\(^d\)Mean airspeed.

Figure 5. Maintenance of a precise altitude during aerobiological sampling 100 m AGL with an autonomous UAV. The UAV flew a point sampling pattern and demonstrated an altitude standard deviation of 1.6 m. The aerobiological sampling devices were opened at time A and closed at time B as indicated by the arrows in the figure.

5.2. Accuracy of Sampling Pattern

Flight paths for the point, line, triangle, rectangle, and figure-8 sampling patterns are shown in Figures 6–10.
Figure 6. Aerobiological sampling with an autonomous UAV using a point pattern consisting of a single GPS waypoint (black dot). Individual flight patterns are shown in panels A (flight 2), B (flight 3), C (flight 8), D (flight 9), and E (flight 10). A combined flight pattern for all five flights is shown in panel F.
Figure 7. Aerobiological sampling with an autonomous UAV using a line pattern consisting of two GPS waypoints (black dots). Individual flight patterns are shown in panels A (flight 11), B (flight 14), C (flight 16), D (flight 17), and E (flight 18). A combined flight pattern for all five flights is shown in panel F.
Figure 8. Aerobiological sampling with an autonomous UAV using a triangle pattern consisting of three GPS waypoints (black dots). Individual flight patterns are shown in panels A (flight 5), B (flight 6), C (flight 7), D (flight 24), and E (flight 25). A combined flight pattern for all five flights is shown in panel F.
Figure 9. Aerobiological sampling with an autonomous UAV using a rectangle pattern consisting of four GPS waypoints (black dots). Individual flight patterns are shown in panels A (flight 4), B (flight 12), C (flight 13), D (flight 15), and E (flight 19). A combined flight pattern for all five flights is shown in panel F.
Figure 10. Aerobiological sampling with an autonomous UAV using a figure-8 pattern consisting of four GPS waypoints (black dots) with the navigation order changed to create a figure-8 pattern. Individual flight patterns are shown in panels A (flight 1), B (flight 20), C (flight 21), D (flight 22), and E (flight 23). A combined flight pattern for all five flights is shown in panel F.
The point (Figure 6) and rectangle (Figure 9) patterns produced the most consistent sampling paths, with high positional accuracy for nearly all of the flights with these patterns. The line pattern (Figure 7) produced the most inconsistent sampling paths, with low positional accuracy for all but one flight. The triangle (Figure 8) and figure-8 (Figure 10) patterns demonstrated consistent sampling paths with moderate positional accuracy for most of the flights.

5.3. Aerobiological Samples

Diverse assemblages of prokaryotic and eukaryotic microorganisms were collected during our flights. Flights conducted with FSM as our sampling medium (Table 1) revealed many different species of *Fusarium* (Figure 11, left), representing a number of potential plant and animal pathogens (Schmale, Dingus, Wood-Jones, Khatibi, & Reinholtz, 2007). Flights conducted with PDA as our sampling medium (Table 1) revealed diverse assemblages of prokaryotic and eukaryotic microorganisms (Figure 11, right), representing a number of uncultured and previously uncharacterized microorganisms that may be new to science (Schmale, Dingus, Wood-Jones, Khatibi, Dickerman et al., 2007).

6. CONCLUSIONS

Autonomous systems technologies have been integrated into a number of UAV systems for various reconnaissance and surveillance missions, but these platforms have only recently been used for civilian applications (Ollero & Merino, 2004). Here, we present a new civilian application for autonomous UAVs—aerobiological sampling above crop fields. We developed an autonomous UAV for aerobiological sampling, and we conducted a total of 25 sampling flights for potential agricultural threat agents representing five different sampling patterns 60–300 m above crop fields at Virginia Tech’s Kentland Farm. This is the first detailed report of the development and application of an autonomous UAV to collect aerobiological samples tens to hundreds of meters above crop fields.

6.1. Sampling Altitude

Aerobiological studies above crop fields often include sampling within the planetary boundary layer (PBL, extending from 50 m to 1 km) or the surface boundary layer (SBL, extending from 10 to 50 m) (Isard & Gage, 2001; Shields & Testa, 1999). The ability to accurately measure the transport of agricultural threat agents in the SBL and PBL requires specialized tools that are robust against large altitude fluctuations during sampling. RC UAVs are often unable to maintain precise sampling altitudes during flight, an obvious consequence of ground-based pilot control. Even small variations in altitude may reflect large differences in observed atmospheric boundary layer dynamics and

![Figure 11](image-url)  
**Figure 11.** Aerobiological samples collected 100 m above crop fields with an autonomous UAV. Colonies of *Fusarium* (left) were rendered from FSM, and microbial assemblages (right) were rendered from PDA.
may significantly impact measurements and model calculations of atmospheric transport. Shields et al. (2006) sampled weed seeds with RC UAVs within a range of 18–38 m (altitude deviations of 9–19 m above or below the target altitude, respectively), and Ayler et al. (2006) collected corn pollen with RC UAVs within a range of about 30 m. Our autonomous UAV exhibited altitude deviations of 2 m on average across all flights when flying the point pattern, resulting in an average sampling range of 4 m. The line pattern (which demonstrated the most inconsistent sampling paths of all of the patterns) exhibited altitude deviations of less than 7.3 m on average across all of the flights. Thus, our autonomous UAV platform, regardless of sampling pattern, has significantly improved altitude accuracy during sampling on the order of 10–30 m compared to RC UAVs.

6.2. Sampling Speed

Large fluctuations in airspeed can significantly alter the volume of air sampled during a sampling mission. When standardizing a sampling interval of time (e.g., 15 min), it is crucial to understand the volume of air that was sampled during that interval. The volume of air sampled is determined in part by the airspeed of the UAV. If the airspeed of the UAV is constantly changing, the volume of air sampled may also change dramatically over the course of the flight. RC UAVs may experience large fluctuations in airspeed, a consequence of delays in throttle adjustments by the ground-based pilot to climb or descend to the target sampling altitude. Shields et al. (2006) observed airspeed standard deviations ranging from 6 to 13 km/h above or below their target sampling speed with RC UAVs, and Ayler et al. (2006) had airspeed deviations within a similar range for their sampling of corn pollen. Our mean airspeeds among all of our flights did not vary more than 1.9 km/h above or below our target sampling speed of 60 km/h. Thus, we have improved airspeed accuracy and consistency by about 4–10 km/h compared to RC UAVs.

6.3. Sampling Pattern

When monitoring the atmospheric movement of agricultural threat agents with a UAV, it is essential to have a sampling pattern that represents the crop field of interest. Small changes in flight pattern (e.g., outside the crop field of interest) pose a number of inherent challenges when attempting to quantify the movement of such agents into or out of crop fields. Maldonado-Ramirez et al. (2005) experienced deviations in flight patterns on the order of fields (tens to hundreds of meters beyond the field of interest) during their sampling of the plant pathogen Gibberella zeae in the PBL. Our point sampling pattern rarely exhibited pattern deviations greater than 50 m, both within and among flights of the same pattern. We did, however, experience considerable pattern noise (shown by sharp pattern deviations) during some of our flights (e.g., Flight 15), which might be explained by fluctuations in weather conditions, interference, or the position of tracked satellites.

Practical flight patterns above agricultural fields are essential for rapid response to agricultural threat agents. To collect samples of such threat agents in a new location, GPS coordinates must be mapped within a new crop field of interest. A simple point pattern may have the most utility when a rapid response is needed. Schmale and Dingus (unpublished observations) were able to measure a GPS waypoint in a new crop field, assign that waypoint to the UAV before takeoff, and conduct a 15-min autonomous sampling mission over that field in less than 30 min. A rectangle pattern in which the corners of a crop field are marked with GPS waypoints may also offer a similar rapid response but over a much larger geographic area. Both the point and rectangle patterns exhibited relatively small deviations in sampling pattern within and among sampling flights and as a result appear to have the most utility for biosecurity applications in individual crop fields. More complex patterns could be constructed in the future to sample over multiple agricultural fields, accounting for variations in field size and topography.

6.4. Aerobiological Samples

We collected a number of potential agricultural threat agents during our autonomous sampling flights. Schmale, Dingus, Wood-Jones, Khatibi, and Reinholdt (2007) determined that some of the fungi collected using FSM represent important plant pathogens of wheat, barley, and corn. Some of these Fusarium spp. may be producers of dangerous mycotoxins, posing a significant threat to humans and domestic animals. Other sampling flights using PDA yielded many different prokaryotic and eukaryotic microorganisms, some of which may be new to science (Schmale, Dingus, Wood-Jones, Khatibi, Dickerman et al., 2007). We are currently attempting...
to predict the spread of these potential threat agents in the atmosphere across large-scale biological and meteorological gradients.

6.5. Future Applications

Autonomous UAVs have the potential to revolutionize aerobiological sampling above crop fields. We have demonstrated the utility of our autonomous UAV platform to improve the precision and accuracy of sampling altitude, sampling speed, and sampling pattern. Our system also reduces pilot fatigue, provides a more predictable sampling environment, and is arguably safer and more efficient than RC UAV platforms that are operated entirely by a ground-based pilot. The development of more sophisticated flight controllers and aerobiological sampling devices may improve our sampling efficiency in the future. Future research using adaptive control theory (Wang et al., 2007) may enable us to further improve the accuracy of our sampling missions and assist in conducting coordinated autonomous sampling flights in multiple boundary layers of the atmosphere.

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REFERENCES


