Coordinated Aerobiological Sampling of a Plant Pathogen in the Lower Atmosphere Using Two Autonomous Unmanned Aerial Vehicles

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Unmanned aerial vehicles (UAVs) are an important tool to track the long-distance movement of plant pathogens above crop fields. Here, we describe the use of a control strategy (coordination via speed modulation) to synchronize two autonomous UAVs during aerobiological sampling of the potato late blight pathogen, Phytophthora infestans. The UAVs shared position coordinates via a wireless mesh network and modulated their speeds so that they were properly phased within their sampling orbits. Three coordinated control experiments were performed August 14–15, 2008. In the first two experiments, two UAVs were vertically aligned at two different altitudes [25 and 45 m above ground level (AGL)] with identical sampling orbits (radii of 150 m). In the third experiment, two UAVs shared the same altitude (35 m AGL) with different sampling orbits (radii of 130 and 160 m). Orbit times did not vary significantly between the two UAVs across all three aerobiological sampling missions, and the phase error during sampling converged to zero within 2 min following the start of the coordinated control algorithm. Viable sporangia of P. infestans were recovered following two of the coordinated flights. This is the first detailed report of autonomous UAV coordination during the aerobiological sampling of a plant pathogen in the lower atmosphere. UAVs operating independently of one another may experience significant sampling variations during the course of a flight. Coordinating the flight of two or more UAVs ensures that the vehicles enter, sample, and exit a spore plume at consistent times. © 2010 Wiley Periodicals, Inc.

1. INTRODUCTION

Unmanned aerial vehicles (UAVs) have generated renewed interest in the field of aerobiology—the study of the flow of life in the atmosphere (Schmale, Dingus, & Reinholdt, 2008). Remote-controlled (RC) UAVs equipped with microbe-sampling devices have been used to track the movement of pollen (Aylor, Boehm, & Shields, 2006), insects (Shields & Testa, 1999), seeds (Shields, Dauer, VanGessel, & Neumann, 2006), and pathogens (Maldonado-Ramirez, Schmale, Shields, & Bergstrom, 2005) above crop fields. Recent work with autonomous (self-controlling) UAVs has highlighted the diversity and function of entire assemblages of microorganisms tens to hundreds of meters above the surface of the Earth (Schmale et al., 2007). Miniaturization of computers, sensors, and other electronic devices has made it possible to equip small UAVs with sophisticated instruments that allow autonomous missions. Commercial off-the-shelf (COTS) autopilots provide adequate control of UAVs under normal flight conditions. Typical modes of operation, such as waypoint navigation and circular flight patterns, are routinely used during aerobiological sampling missions (Schmale et al., 2008). More advanced applications have utilized time-optimal path planning algorithms to optimize the sampling effort during aerobiological sampling (Techy, Woolsey, & Schmale, 2008).

Multiple RC UAVs have been flown simultaneously at different altitudes to take measurements that help model the long-distance movement of pollen in the lower atmosphere (Aylor et al., 2006). UAVs have also been flown simultaneously at similar altitudes to image large geographic areas during surveillance missions (Wise & Rysdyk, 2006). In both of these cases, the UAVs operated independently of one another, relying on positional information from the ground-based pilots and/or the autopilots to avoid collision. New and exciting applications in aerobiology seek to leverage the cooperative control of two or more autonomous UAVs simultaneously (Schmale et al., 2008; Techy, Paley, & Woolsey, 2009; Techy et al., 2008; Techy,20335
The sampling experiments described in this paper were part of a larger project focused on the validation of atmospheric dispersion models used to predict the motion of *P. infestans* sporangia in the lower atmosphere. A potato field covering approximately 1.5 acres of NY118 potatoes was established to provide a sufficiently large, continuous plant canopy to serve as the source of inoculum for the experiments. The field was inoculated with a domestic strain of *P. infestans* 2 weeks prior to the experiments to allow the disease to spread across the potato field. One way the disease may spread from infected plants to healthy plants is by aerial transport. Figure 1 is a photograph of an infected potato leaf taken at Virginia Tech's Kentland Farm during the experiments. The disease (potato late blight) results in the formation of necrotic lesions on potato leaves that are surrounded by sporangia. The sporangia are released into the atmosphere in the early morning hours and may be picked up by turbulent airflow over the plant canopy and reach higher altitudes within the planetary boundary layer.

One goal of the project is to predict the long-distance transport of *P. infestans* in the atmosphere. Lagrangian-stochastic (LS) simulation models have been successfully applied to model the movement of sporangia within meters of infected potato fields (Aylor et al., 2001). The accuracy of the collected data is crucial in these validation efforts. The sporangia concentration estimate, \( C \) (number of sporangia per cubic meter), at different altitudes above the plant canopy is assessed in a two-step process. Because the area source strength, \( Q \) (number of sporangia per square meter per second), is crucial in any plume modeling effort, this has to be estimated first. This is done by estimating the total number of sporangia in the field at the beginning of the day (standing crop of sporangia) and distributing it according to the diurnal sporangial release pattern. Sporangia-collating “Rotorod-towers” are employed to collect concentration data at heights 0.5, 1, and 3 m above the ground. These concentration measurements can be used to reconcile with the estimated data to obtain a more accurate estimate of \( Q \). The estimate of \( Q \) is then used in the simulation models to find the calculated concentration estimates at different altitudes.

To measure the concentration and viability of sporangia at several tens to hundreds of meters above ground, UAVs were used that were fitted with sporangia-sampling devices mounted under the wings. UAVs are able to sample large volumes of air in a relatively short time (Maldonado-Ramirez et al., 2005). Although millions of sporangia may be released into the air across a large infected potato field, they may be sparsely distributed at increased distances and altitudes from the source. Hence, sampling a large volume of air during a sampling experiment is necessary. The sampling devices onboard the UAVs collect a cumulative sample across an entire flight that can later be analyzed in the laboratory. As the sample is essentially the accumulation of sporangia that are collected during a certain time interval, it is crucial to have consistent samples during the experiment. The sampling patterns we report in this paper were

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**Figure 1.** Late blight of the potato, caused by the fungus-like organism *P. infestans*, in a potato field at Virginia Tech’s Kentland Farm. Sporangia form in a cloudy halo around necrotic lesions and are released in turbulent winds for transport in the atmosphere.

Woolsey, & Schmale, 2009). Multiple UAVs flying coordinated, time-synchronized paths may permit a more precise assessment of microbial stratification in the lower atmosphere and may enable a more accurate measure of pathogen concentrations over crop fields.

In this paper, we describe the use of a cooperative control strategy (coordination via speed modulation) to synchronize two autonomous UAVs during aerobiological sampling of *Phytophthora infestans*, causal agent of late blight disease of potatoes and tomatoes. *P. infestans* caused the Irish Potato Famine: a devastating episode in history that resulted in the deaths of over one million people (Schumann & D’Arcy, 2000). This fungus-like organism produces spore-bearing structures called sporangia on the surface of potato leaves (Figure 1) (Schumann & D’Arcy, 2000). The sporangia are released into the air during the morning hours (Aylor, Fry, Mayton, & Andrade-Piedra, 2001) and may be transported over long distances in the atmosphere to new locations where they may infect healthy plants and cause disease (Skelsey, Kessel, Holstag, Moene, & van der Werf, 2009). One of the main goals of our ongoing work is to develop new technologies to detect, monitor, and forecast the movement of *P. infestans* in the lower atmosphere. The control strategy demonstrated in this paper improves the precision and accuracy of aerobiological sampling with UAVs: multiple vehicles operating at one or more altitudes can enter, sample, and exit a pathogen plume at consistent times over the course of a sampling mission.

2. FIELD EXPERIMENTS

The sampling experiments described in this paper were part of a larger project focused on the validation of atmospheric dispersion models used to predict the motion of *P. infestans* sporangia in the lower atmosphere.

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defined prior to the missions and consisted of circular orbits around the potato field.

As part of the field trials, three coordinated control experiments were performed at Virginia Tech’s Kentland Farm in Blacksburg, Virginia, August 14–15, 2008. UAV flights were coordinated during peak sporangia release (approximately 8 a.m. to 1 p.m. daily) from the inoculated potato field. The sampling was performed by two modified Sig Rascal 110 airplanes as described in Section 3. The UAVs coordinated their flight activity to simultaneously collect sporangia of \( P. \) infestans in the lower atmosphere using the orbit controller discussed in Section 4.

Coordinating the flight of the UAVs ensures that the samples are consistent between the two flights, so that measurements can be compared with each other. If the flights are not coordinated, then the measurements are independent (e.g., the sampling conditions of the UAVs may change from orbit to orbit). For our experiments, coordinated flight patterns were selected to assess the vertical (two UAVs operating at different altitudes) and horizontal (two UAVs operating at the same altitude but with different orbits) distributions of \( P. \) infestans sporangia near the infected potato field.

3. UAV PLATFORMS

The UAV platforms were based on a modified Sig Rascal 110 RC airframe. This is a high-wing, box-fuselage aircraft with a wing span of 110 in. (2.974 m). The airframe weighs approximately 14 lb (6.35 kg) empty and can carry an additional 10 lb (4.536 kg) of payload. The payload bay of the airplanes was modified to host an onboard computer and the flight critical electronics, including the autopilot. The task of the autopilot was to manage single vehicle control by sending control signals to the control surface servos. Communication with the ground station was established through a 900-MHz radio link. The addressing of each autopilot in the network was implemented using flow control of data streams, in which the ground station polls each avionics unit in a round-robin fashion. The multihomed communication implemented in the avionics allowed the autopilot to receive packets from two sources: the 900-MHz radio link and an RS-232 serial connection. This allowed the autopilot to accept commands for each of its control loops from an onboard computer that managed higher level coordination tasks and multivehicle communication. Speed commands were sent to the autopilot to achieve tracking and coordination, and the altitude loop command was constant.

The payload bay of the Sig Rascals housed a PC-104+ computer EmETX-i701 with an Intel Pentium 4, 1.4-GHz processor with 2 MB of L2 cache, and 1 GB of DDR SDRAM. The computer had a PCMCIA extender board, which was used to host the wireless mesh network card. The principal advantages of a mesh network are its ability to quickly reacquire if the communication is lost and the ability to achieve communication between nodes that do not have a direct link by routing the packets between other connecting nodes. Each UAV had the ability to broadcast its position information on the network at 20 Hz using Joint Architecture for Unmanned Systems (JAUS) interoperable packets through User Datagram Protocol (UDP). On the basis of the position information of other UAVs, each UAV could calculate the necessary commands for coordinating its motion in a decentralized way. The commands were then sent to the autopilot for execution.

The UAVs carried special sporangia-sampling devices that could be opened and closed during flight (Figure 2). When the samplers were open, the surfaces of the sample devices were exposed to the ambient airflow, allowing sporangia of \( P. \) infestans to be deposited on them. In the experiments described in this paper, the samplers contained polycarbonate filter paper coated with 50% glycerol placed on the center of 60-mm, 1.5% water agar plates.

4. COORDINATED CONTROL VIA SPEED MODULATION

In this section, we describe a coordination algorithm that uses speed commands to control the angular separation between two identical UAVs. Coordinating the motion of multiple vehicles is a current topic within the control research community. For example, steering laws were derived in Justh and Krishnaprasad (2004) to drive a set of particles to certain synchronized patterns using decentralized control laws. The control laws can be used to stabilize parallel motions, when all vehicles travel in the same inertial direction, or circular patterns, when all vehicles orbit around the same point. Using the same particle model, stabilizing control laws were derived in Sepulchre, Paley, and Leonard (2007) to drive a set of particles to a variety of motion patterns known as relative equilibria. The control laws
were applied in large-scale ocean sampling experiments to coordinate the motion of multiple underwater gliders during an experiment (Paley, Leonard, Sepulchre, Grunbaum, & Parrish, 2007; see also Zhang, Fratantoni, Paley, Lund, & Leonard, 2007). The methods were later extended to allow synchronization along convex curves (Paley, Leonard, & Sepulchre, 2008) or synchronization in winds (Paley, 2008). The methods were also applied to synchronize the motion of UAVs to perform environmental sampling in the presence of winds (Techy, Paley, et al., 2009) and to perform perimeter surveillance tasks by a collection of UAVs (Paley, Techy, & Woolsey, 2009). Other authors have also addressed the coordination of multiple vehicles for use in forest fire scenarios (Sujit, Kingston, & Beard, 2007), where the UAVs were controlled to a desired formation by controlling the turn rate of the vehicles. A similar approach is described in Rysdyk, Lum, and Vagner (2005), where the flight of two autonomous UAVs is coordinated using turn rate inputs. Lyapunov vector fields have been used to guide UAVs to loiter circles around moving targets (Frew & Lawrence, 2005).

Most of the work mentioned above assumes constant-speed vehicles: this restriction allows coordination by turn rate commands only. Alternatively, one may control the speed of the UAVs to coordinate the flight of the vehicles. In this paper we present experimental results using a coordination algorithm to synchronize the flight of two UAVs. The algorithm is referred to as coordination via speed modulation, because the synchronized state is achieved by applying small differential changes in the speed commands of each UAV to allow for phase synchronization. In this approach, we assume that the tracking problem is handled by the autopilot and both UAVs are on the desired orbit. A similar orbit controller was concurrently developed independently by Frew, Lawrence, and Morris (2008).

Consider the kinematic model of two UAVs:

\[
\begin{align*}
\dot{x}_N &= v_N \cos \psi, \\
\dot{y}_E &= v_N \sin \psi, \\
\dot{\psi} &= v,
\end{align*}
\]

where \(x_N(t)\) and \(y_E(t)\) are the inertial north and east coordinates with respect to some fixed reference frame, \(\psi(t)\) is the heading of the vehicles, and \(v_N(t)\) is the airspeed. We assume that the autopilot manages the tracking of a circle of radius \(R\) and ensures that the vehicle stays on the path even in the presence of external disturbances (such as wind gusts). Assume that the inertial origin is located in the center of the circle of interest to track (see Figure 3). Let us denote the “phase angle” of the vehicles by

\[
\theta_k(t) = \arctan \left( \frac{y_{E_k}(t)}{x_{N_k}(t)} \right), \quad k = 1, 2,
\]

Figure 3. UAVs traveling along a circular flight pattern. The desired phase separation \(\theta^*\) is achieved by controlling the speed of the vehicles.

and use a simple particle kinematic model for motion around a circle of radius \(R\) (as tracked by the autopilot):

\[
\dot{\theta}_k(t) = \omega_k(t) = \frac{v_k(t)}{R}.
\]

Define

\[
\delta \theta(t) = \theta_2(t) - \theta_1(t) - \theta^* \quad \delta \theta(t) \in [-\pi, \pi]
\]

as the phase error, where \(\theta^* \in [0, \pi]\) is the desired phase advantage of UAV2 to UAV1. We assume that

\[
v_k(t) = V_a + u_k(t), \quad k = 1, 2,
\]

where \(V_a\) is the desired average airspeed and \(u_k\) is a control signal. Select the control signal as

\[
u_k(t) = K(-1)^k \sin[\delta \theta(t)], \quad k = 1, 2,
\]

where \(K > 0\). Then the phase error dynamics takes the form

\[
\dot{\delta \theta}(t) = -\frac{2K}{R} \sin[\delta \theta(t)].
\]

Proposition 4.1. The origin of system (6), corresponding to the desired phase arrangement, is almost globally asymptotically stable.

The proof is a simple application of Lyapunov’s direct method to system (6), with the Lyapunov function \(V(t) = \frac{1}{2}\delta \theta(t)^2\), and LaSalle’s invariance principle (Khalil, 2002).

To eliminate errors due to slight differences in the calibration of the pitot tube readings, an integral channel can be added as follows. Define

\[
e_k(t) = (-1)^k \sin[\delta \theta(t)], \quad k = 1, 2.
\]

Define a “proportional-integral (PI)” control signal for the \(k\)th vehicle:

\[
u_k(t) = K_p e_k(t) + K_i \int_0^t e_k(t) dt, \quad k = 1, 2.
\]
The time scale for achieving the desired speed is governed by the autopilot and the system parameters and is on the order of seconds. The time scale for synchronization is orders of magnitude slower. This time-scale separation allows us to treat the UAV dynamics and the synchronization dynamics independently and assume that the desired velocity can be instantaneously achieved. Proper choice of gains (see also Section 7) ensures that the synchronization algorithm does not degrade the autopilot’s inherent stability.

5. PROCESSING OF AEROBIOLOGICAL SAMPLES

Sampling plates remained closed during takeoff and landing, and they were covered and placed in a cooler for transport to the laboratory immediately following the coordinated flights. The filter paper was cut into four pieces in a biosafety cabinet, and the exposed surface was placed in direct contact with disinfested potato leaflets collected from the greenhouse (Figure 4). Two hundred microliters of sterile deionized water was added to the filter paper to encourage zoospore formation and resulting infection. Cultures were incubated for 3–5 days in the laboratory at ambient room temperature and examined with a microscope to observe symptoms of late blight and signs of *P. infestans*.

6. STATISTICAL ANALYSES

We hypothesized that our control strategy would minimize the variation in orbit times between two UAVs during an aerobiological sampling mission. To test this hypothesis, we used an analysis of variance (ANOVA) to examine significant differences in orbit times between UAVs during each of the aerobiological sampling experiments. Statistical analyses were conducted with SAS system for Windows (Release 9.1.2; SAS Institute Inc., Cary, North Carolina).

7. EXPERIMENTAL RESULTS

7.1. Results from Three Coordinated Control Experiments

Three coordinated control experiments were performed on August 14–15, 2008 (Table I). The first experiment was conducted on August 14, 2008, 9:30 a.m. EST. The second and third experiments were conducted at 9:30 a.m. and 11:30 a.m. EST on August 15, 2008. Each of the experiments involved two autonomous UAVs that coordinated their flights by sharing their position information through the wireless mesh network. In the first two experiments, two UAVs were vertically aligned at two different altitudes [25 and 45 m above ground level (AGL)] with identical sampling orbits (radii of 150 m). In the third experiment, two UAVs shared the same altitude (35 m AGL) with different sampling orbits (radii of 130 and 160 m).

In both experiments the UAVs used the speed control algorithm (4) and (7) to coordinate their motion along the flight path. The gains for the speed control algorithm (7) were chosen as $K_p = 4$ and $K_i = K_p/80$. The proportional gain was chosen to increase the velocity of the vehicle by 2 m/s if the vehicle’s phase lag is 30 deg. The integrator was implemented with antiwindup that limits the minimum airspeed at 18 m/s and the maximum airspeed at 25 m/s. For the second experiment, in which the UAVs were following concentric orbits, the desired average airspeeds $V_a$ in Eq. (7) were different to make sure that the UAVs flew with a similar angular rate in steady state. The desired angular separation in Eq. (3) was chosen $\theta^* = 0$. This corresponds to the UAVs flying with the same phase $\phi_1(t) = \phi_2(t)$.

7.1.1. Experiment 1: August 14, 2008, 9:30 a.m. EST

A three-dimensional (3D) telemetry plot from the first experiment is shown in Figure 5(a). The autopilot holds the altitude at the desired value with high precision. For both
Table I. Summary of the flight experiments conducted August 14–15, 2008.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Date and time</th>
<th>Mean AGL (m)</th>
<th>Radius of orbit (m)</th>
<th>Mean airspeed (m/s)</th>
<th>Sample time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT5</td>
<td>08/14/08, 9:30 a.m.</td>
<td>43</td>
<td>150</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>LT6</td>
<td>08/14/08, 9:30 a.m.</td>
<td>25</td>
<td>150</td>
<td>21</td>
<td>17</td>
</tr>
<tr>
<td>LT8</td>
<td>08/15/08, 9:30 a.m.</td>
<td>25</td>
<td>150</td>
<td>21</td>
<td>19</td>
</tr>
<tr>
<td>LT9</td>
<td>08/15/08, 9:30 a.m.</td>
<td>45</td>
<td>150</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td>LT10</td>
<td>08/15/08, 11:30 a.m.</td>
<td>40</td>
<td>160</td>
<td>26</td>
<td>16</td>
</tr>
<tr>
<td>LT11</td>
<td>08/15/08, 11:30 a.m.</td>
<td>34</td>
<td>130</td>
<td>19</td>
<td>16</td>
</tr>
</tbody>
</table>

Viable sporangia of \( P. \text{infestans} \) were collected during flights LT5 and LT6. During the experiments the nominal AGL altitudes were 25 and 45 m for the vertically aligned flights and 35 m for the concentric flights.

UAVs, the standard deviation for altitude was less than 1.33 m. In Figure 5(b) we can see the time history of the phase error \( \delta \theta(t) \). After the algorithm starts, the phase error converges to zero.

7.1.2. Experiment 2: August 15, 2008, 9:30 a.m. EST

A 3D telemetry plot from the second experiment can be seen in Figure 6(a). In Figure 6(b) we can see the time history of the phase error \( \delta \theta(t) \). Similarly to the first flight experiment, the UAVs hold the desired altitude with high precision and converge to a phase-synchronized state.

7.1.3. Experiment 3: August 15, 2008, 11:30 a.m. EST

In the third experiment, the UAVs were flying at the same altitude, 35 m AGL. One of them was flying on a \( R = 130 \)-m-radius circular flight path, and the other one was flying on a 160-m radius. The telemetry plot and phase error history from the experiment are shown in Figures 7(a) and 7(b), respectively.

7.2. Collection of Viable Sporangia of \( P. \text{infestans} \)

Viable sporangia of \( P. \text{infestans} \) (i.e., sporangia that are able to cause disease on greenhouse-grown potatoes) were recovered from two of the coordinated flights, LT5 and LT6 (Figure 4, right). We did not recover viable sporangia of \( P. \text{infestans} \) from the other sampling missions, but ongoing DNA-based methodologies are currently being optimized in the Schmale laboratory to detect and quantify sporangia of \( P. \text{infestans} \) from these aerobiological samples.

7.3. Variations in Orbit Times and Sampling Altitudes

Orbit times did not vary significantly between UAVs for each of the three experiments (Experiment 1, \( P = 0.13 \); Experiment 2, \( P = 0.64 \); Experiment 3, \( P = 0.46 \)). These
results are consistent with our hypothesis that the coordina-
tion of two UAVs reduces the variation in orbit times dur-
ing an aerobiological sampling mission.

8. CONCLUSIONS

In this paper a UAV coordination strategy is discussed that
supports ongoing investigations centered on the spread of
the potato pathogen Phytophthora infestans. The coordina-
tion algorithm applies small changes in the airspeed of
two UAVs to achieve spatial synchrony along orbital flight
paths. For all three experiments, the phase error stayed
bounded \(|\delta \theta(t) < 10\ \text{deg}|\) and orbit times did not vary sig-
nificantly between UAVs. Thus, our control strategy min-
imized the phase difference between the UAVs such that
measurements between the vehicles are comparable and
not independent.

UAVs operating independently of one another may ex-
xperience significant sampling variations during the course
of a flight. Coordinating the flight of two or more UAVs en-
sures that the vehicles enter, sample, and exit a spore plume
at consistent times. Our coordinated patterns were defined
to assess the vertical and horizontal distribution of P. infes-
tans sporangia near the infected potato field. The vertical
distribution of sporangia above the potato field was as-
sumed using two UAVs that were separated vertically by a
Figure 8. Photograph of two autonomous UAVs in a synchronized aerobiological sampling mission. Photograph taken on August 14, 2008.

predefined standoff distance. Both UAVs followed the same ground path during the flight, allowing us to compare collections at two different altitudes. The horizontal distribution of *P. infestans* sporangia was assessed using two UAVs flying at the same altitude separated by two different predefined orbits (concentric circles) centered on the same origin. This sampling effort allowed us to compare collections of sporangia at two different distances from the source. Such coordinated measurements have the potential to provide information on the shape of the sporangia plume. Unexpected sample variation might suggest that one of the UAVs was too high for that particular sampling orbit to even sample inside the spore plume, which may happen if the spore plume is flat and elongated in the wind direction.

The methods described in this paper were tested in three field experiments focusing on the spread of *P. infestans* on August 14–15, 2008. Figure 8 is a photograph of two autonomous UAVs in a coordinated sampling mission on August 14, 2008. During these experiments, two of the UAVs returned with samples that contained viable sporangia (able to cause disease on greenhouse-grown potato leaves), collected at 25 and 45 m AGL. This is the first published report of the collection of viable sporangia of *P. infestans* with coordinated, autonomous UAVs, providing important clues about the role of long-distance aerial transport of *P. infestans* in regional late blight epidemics. Previous work has shown that sporangia may survive hours in the atmosphere, depending on their cumulative exposure to varying degrees of solar radiation (Mizubuti, Aylor, & Fry, 2001). Knowledge of the atmospheric transport of *P. infestans* sporangia is a prerequisite to the development of rational and informed approaches for managing potato late blight (Aylor, 1999), yet little is known about the limits of long-distance transport (0.2–5 km) for the pathogen (Aylor, 2001). New, more aggressive strains of *P. infestans* could be introduced into the United States from other parts of the world (Fry et al., 1992), and these new strains might be transported 10–100 km through the atmosphere to new geographical locations.

Our aerobiological sampling strategy to track the movement of *P. infestans* in the lower atmosphere with UAVs is limited by relatively long sampling intervals (16–19 min), the coordination of only two vehicles, and ground-based detection of cumulative collections of sporangia. Future coordinated aerobiological sampling missions with UAVs will need to consider shorter sampling intervals, larger vehicle swarms, and onboard near-real-time pathogen detection capabilities. Our demonstration of a simple, effective control strategy to coordinate the control of UAVs is an important interim step toward developing high-resolution, time-dependent maps of spore plumes and localizing the potential source(s) of a potato late blight epidemic. Mathematical models of varying complexity may be employed in the future to predict the trajectories of the sporangia from infected potato fields, given ambient wind and other environmental conditions (Aylor et al., 2001; Skelsey et al., 2009). These models may assist in determining the risk of late blight infection in the future, ultimately guiding agricultural stakeholders to effective plant health management decisions, such as the application of appropriate fungicides.

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