THE USE OF UNMANNED AERIAL VEHICLES AND WIRELESS SENSOR NETWORK IN AGRICULTURAL APPLICATIONS

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ABSTRACT

The application of pesticides and fertilizers in agricultural areas is of prime importance for crop yields. The use of aircrafts is becoming increasingly common in carrying out this task mainly because of its speed and effectiveness in the spraying operation. However, some factors may reduce the yield, or even cause damage (e.g. crop areas not covered in the spraying process, overlapping spraying of crop areas, applying pesticides on the outer edge of the crop). Climatic conditions, such as the intensity and direction of the wind while spraying add further complexity to the control problem. In this paper, we describe an architecture based on unmanned aerial vehicles (UAVs) which can be employed to implement a control loop for agricultural applications where UAVs are responsible for spraying chemicals on crops. The process of applying the chemicals is controlled by means of the feedback obtained from the wireless sensor network (WSN) deployed on the crop field. The aim of this solution is to support short delays in the control loop so that the spraying UAV can process the information from the sensors. We evaluate an algorithm to adjust the UAV route under changes in wind intensity and direction. Moreover, we evaluate the impact of the number of communication messages between the UAV and the WSN. Results show that the adjustment of the route based on the feedback information from the sensors could minimize the waste of pesticides.

1. INTRODUCTION

Unmanned aerial vehicles have become cheaper because many control functions can be implemented in software rather than having to depend on expensive hardware. This even allows multiple UAVs to be used for a single application. In this case, the UAVs must have communication facilities so that they can communicate with each other. This can easily be achieved by equipping an UAV with a wireless mesh node. In this scenario, the UAV swarm can be considered to be a highly mobile wireless mesh network [1, 2].

Several UAVs then form a swarm, where they can perform useful work in a collaborative way. A number of applications have been proposed for UAV swarms such as forming an ad-hoc communication network [3, 4] in case there is a disaster, retrieving sensor information from sensors deployed in areas that are not easy for humans to access, or even transmitting live audio/video from sports events involving fast-moving people, such as bicycle races or skiing competitions.

In this paper we propose an architecture based on unmanned aerial vehicles (UAVs) that can be employed to implement a control loop for agricultural applications where UAVs are responsible for spraying chemicals on crops. The process of applying the chemicals is controlled by means of the feedback from the wireless sensors network deployed at ground level on the crop field. The aim of this solution is to support short delays in the control loop so that the UAV spraying can process the information from the sensors. Furthermore, we evaluate an algorithm to adjust the UAV route under changes in the wind (intensity and direction) and the impact related to the number of messages exchanged between the UAV and the WSN. The information retrieved by the WSN allows the UAV to confine its spraying of chemicals to strictly designated areas. Since there are sudden and frequent changes in environmental conditions the control loop must be able to react as quickly as possible.

This paper is organized as follows: In Section 2 we discuss related work on mobile ad-hoc network routing protocols and topology control for unmanned aerial vehicles. Section 3 outlines the proposed method. Section 4 describes the evaluation of all performed experiments. The final section concludes the paper and shows some future perspectives.

2. RELATED WORK

Mobile ad-hoc network (MANET) routing protocols can be divided into the following key groups: (i) flat proactive routing, (ii) on-demand respective reactive routing, (iii) hybrid schemes, (iv) geographic routing and (v) opportunistic routing. Proactive (table-driven) routing protocols maintain their routing information independently of communication needs. State updated messages are sent periodically or when the network topology has changed. Thus, a source node gets a routing path immediately if it needs one. This results in low latency and makes the protocols suitable for real-time traffic. With the aid of proactive routing protocols, nodes proactively update their network state and maintain a route regardless of whether data traffic exists or not. The main drawback of these routing protocols is the high overhead to keep the network topology information up-to-date. All the nodes require a consistent view of the network topology.

Reactive (on-demand) routing only establishes routes if they are required. This saves energy and bandwidth during periods of inactivity. But a significant delay may occur as a result of the on-demand route discovery. Compared to the proactive ad-hoc routing protocols, one advantage of the reactive routing protocols is the lower control overhead. Furthermore, reactive routing protocols have better scalability than proactive routing protocols in MANETs. However, reactive routing protocols may experience long delays for route discovery before they can forward data packet. Reactive protocols perform well in networks with light load.

Geographic routing (GR) protocols assume that a source knows its position and can determine the position of the destination. Moreover, each node knows its neighbors' positions. In comparison to flooding-based approaches, GR routing has a reduced overhead for route discovery. GR protocols only require information about neighbor location to route packets and do not need to maintain per-destination information. Most GR protocols use greedy forwarding as the main method to select the next hop. To avoid dead-ends in the routing path, face-routing has been proposed to route around a void [5, 6].

Opportunistic routing (OR) [7, 8] assumes that an end-to-end communication path may frequently be disrupted or may not exist in a MANET at anytime. The routing mechanism forwards the message towards the destination on a hop-by-hop basis and the next hops are selected according to protocol-specific characteristics. This means that it is not essential to have a stable end-to-end connection from the data source to the destination. Packets are forwarded even if the topology is continuously changing. Normally, OR protocols send a packet not only to a single next hop but also to multiple neighbors simultaneously. One or more of the receiving nodes then forward the packet towards the destination. In most OR protocols, the sender has to calculate a forwarding set, which defines a priority sequence for the possible forwarding neighbor nodes. Depending on the received priority sequence, the neighbor nodes decide which node the packet has to be forwarded to. The main problem of OR is how to calculate a forwarding set that can minimize the transmission costs to the destination.

The absence of a central infrastructure implies that a MANET does not have an associated fixed topology. Indeed, an important task of a mobile ad-hoc network consisting of geographically dispersed nodes, is to determine an appropriate topology for which high-level routing protocols can be implemented. This problem has recently been investigated, particularly in the area of wireless sensor networks [1, 9]. Topology control protocols for WSNs are mainly employed for controlling and adapting the transmission power. The question of exploiting the mobility of nodes has not yet been investigated. There have still been no research studies on topology control for highly mobile communication scenarios.

3. UAVS FOR AGRICULTURAL APPLICATION

Figure 1 shows the application scenario outlined in this paper. The currently concept scenario have one UAV and 42 ground sensors. A UAV is used to spray chemicals on an agricultural field. However, the neighboring field, which may belong to another owner, must not be sprayed. Moreover, the UAV must respect their lane of operation (boundary). If the UAV used for spraying comes too close to the neighboring field, or if there is a sudden change in the direction of the wind, the chemicals might fall on the neighboring field and this must be avoided. To be able to adjust the trajectory, we propose that the UAV gets information from the WSN deployed in the crop field. Whether a sensor detects an excessive concentration of chemicals, the spraying UAV will be directed away from the border.

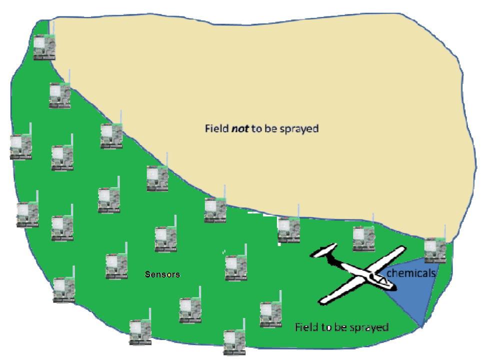


Fig. 1. Sample of application scenario.

The algorithm to adjust the UAV route works as follows: periodically, the UAV broadcasts messages to the sensors on the fields to check the amount of pesticides being used. If the sensor receives the message, it responds with a message reporting the amount of measured pesticide and its position. With this information, the UAV can take a decision about whether to change its route or not. The route is changed when the amount of chemicals perceived by the sensor does not match with the proposed threshold (each type of chemical should have its own threshold).

The system implementation (currently in a simulation model) has been divided into two modules: (i) the *Behavioral Module* and (ii) the *Chemical Dispersion Module*. In the *Behavioral Module* we simulate the communication between the WSN positioned in the field and the UAV, using OMNeT++[1] with the MiXiM[2] framework. The *Dispersion Module* was developed by means of Python[3] and SDL[4] library. The two modules run simultaneously, in an integrated way[5] with socket-based communication. The *Behavioral Module* sends the current position of the UAV (x,y,z) to the *Dispersion Module* along with the UAV orientation and velocity (θ,v). Furthermore, in the *Behavioral Module*, the wind modelling is performed, which emulates changes in wind direction and velocity, and provides information to the *Dispersion Module* about changes in the environment.

The *Dispersion Module* performs the calculation of the fall of the chemicals, by obtaining the position and fall time of each drop. The WSN, in turn, identifies the amount and position of the chemicals and returns this information to the *Behavioral Module*. Periodically, the UAV sends a broadcast message to the ground sensor nodes, requesting concentration in its area. The ground sensor nodes that receive this message, connect to the *Dispersion Module* and request its concentration using their positions (x, y, z) as parameters. In this way, they can respond by giving the concentration in this area to the UAV. By means of these response messages from the ground nodes, the UAV can call a decision manager instance to compute its decision and then change its route if necessary.

4. EVALUATIONS AND RESULTS

Whereas we are evaluating the algorithm to adjust the UAV route, seeking to have a better area of coverage even with climatic changing, a wind dataset with real data regarding the orientation and intensity of the wind was used. During the simulation, the wind changed periodically by means of this data. The UAV was programmed to fly over the entire crop while spraying chemicals. Moreover, we seek to evaluate whether the number of message exchanges between the UAV and the WSN improve the system performance or not. The different parameter sets evaluated can be seen in Table 1. We evaluate the system with changing in the wind (every 15 s and 30 s), with changing in the number of messages between the WSN and the UAV (every 10 s and 30 s), and, using or not the proposed algorithm. We run 10 times each parameter set, with different random seeds. Results can be seen in Fig. 2. In these simulations, the terrain size has been settled out with 1100 m by 100 m. The area to be spayed is a portion of the terrain, with 1000 m by 50 m. The number of sensors inside the crop field is 42. The UAV velocity and operating height is 15 m/s and 20 m, respectively.

Table 1. Parameter sets evaluated (with different weather and system characteristics).

Eval.	Changing in wind (every)	Number of messages (every)	Using proposed algorithm
E1	30 s	-	No
E2	30 s	30 s	Yes
E3	30 s	10 s	Yes
E4	15 s	-	No
E5	15 s	30 s	Yes
E6	15 s	10 s	Yes

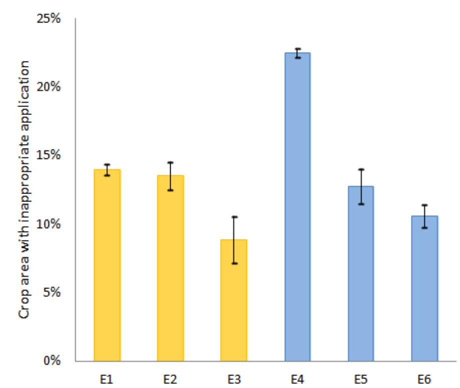
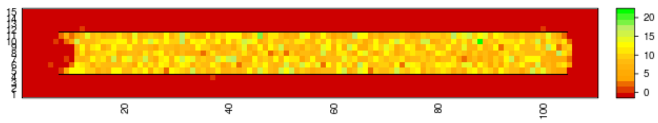


Fig. 2. Amount of chemicals sprayed outside the boundary (average $\pm$ confidence interval). Parameters from evaluation 1 (E1) to evaluation 6 (E6) can be seen in Table 1.

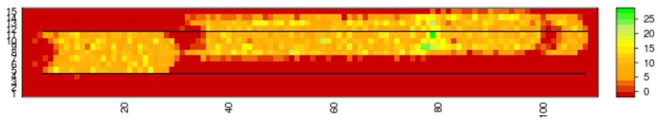
We can see in Figure 2 that the two best results are E3 and E6. This makes sense due to the fact that both E3 and E6 are the evaluations using more messages (every 10 s). Also, we can see that E1, E2 and E5 are quite similar in the graphic; it shows that the use of no message (and therefore no algorithm) or the use of a small number of messages (every 30 s) do not help the system with the currently configurations of crop size, wind types and velocity. Although there seems to be a small reduction from E1 to E2 and E5, a statistical analysis using *t*-test showed that they are statistically equivalent (using 0.95 of confidence). The *p*-values from the *t*-test between $\{$(E1,E2),(E1,E5),(E2,E5)$\}$ are $\{$0.44, 0.10, 0.38$\}$. Figure 2 shows, in orange, wind changing every 30 s and in blue, changing in the wind every 10 s.

The results E1 and E4 show, respectively, changing in wind every 30 s and 15 s and without any type of adjustment in the route. As expected, it shows the worst results. Evaluation E4 is the worst among all, because it has changes in the wind every 15 s, while E1 has less changes, i.e. every 30 s. Fig. 3 shows the representation of the chemicals sprayed in

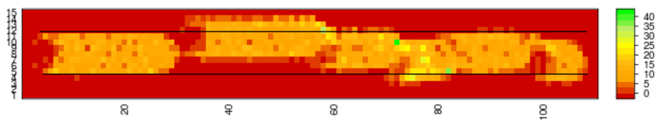
[1] OMNeT++ Network Simulation Framework, http://www.omnetpp.org
[2] MiXiM project, http://mixim.sourceforge.net
[3] Python Programming Language, http://www.python.org
[4] Simple DirectMedia Layer, http://www.libsdl.org
[5] Simulation video available at http://youtu.be/4wFJZZEYAKM



(a)



(b)



(c)

Fig. 3. Representation of the chemicals sprayed in the crop. (a) Evaluation without wind. It shows almost no chemicals outside the lane. (b) Evaluation with wind changes every 15 s and no adaptation in the UAV route - we can see that the wind makes the chemicals fallen outside the boundary lane. (c) Evaluation with wind changes every 15 s and using the algorithm to adapt the UAV route - we can see that the algorithm adjusts the UAV trying to fit the chemicals in the boundary lane. Thin black lines inside the red area shows the defined boundaries.

the crop field in some of the evaluations. In Fig. 3(c) we can see how the algorithm adjusts the UAV route trying to fit the chemicals in the boundary lane.

5. CONCLUSIONS AND FUTURE WORK

In this paper we have described an architecture based on unmanned aerial vehicles (UAVs) that can be employed to implement a control loop for agricultural applications where UAVs are responsible for spraying chemicals on crops. The process of applying the chemicals is controlled by means of the feedback from the wireless sensors network deployed at ground level on the crop field. Furthermore, we have evaluated an algorithm to adjust the UAV route under changes in the wind (intensity and direction) and the impact related to the number of messages exchanged between the UAV and the WSN.

Based on the results we can see that using the currently terrain configuration, the use of messages every 30 s does not improve the system. But, the use of messages every 15 s does improve it. In experiments E1 to E3 we have a reduction of 13.95% to 8.86% and in E4 to E6 we have a reduction of 22.47% to 10.57% considering the waste of chemicals. Although the platform is still in a developmental stage, it is already possible to simulate different scenarios.

The next stages of this project will be as follows: (i) to model a realistic type of behavior for the chemicals in the air; (ii) to implement the application layer of the UAV so that it can actively change its route on the basis of the information obtained from the ground sensor; and (iii) model the simulation through a UAV swarm technique. Following the development of these next stages, we plan to reduce the amount of chemicals applied outside of the designated area, and maximize the space where they are applied on the crops.

6. ACKNOWLEDGMENTS

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