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Framework for Biological Control with Unmanned Aerial Vehicles*

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***Abstract*—Agricultural pests and diseases can cause financial losses on the scale of millions per year and threaten food security. Biological control (BC) is a natural phenomenon to mitigate a particular population of pests, making them less abundant and harmful. The use of Unmanned Aerial Vehicles (UAVs) as a platform to support BC is promising due to the low cost, high efficiency, and wide application range. UAV coverage path planning is necessary to an effective dispersion over an agricultural area. However, in many cases, this planning is carried out empirically by pilots in the field. It is necessary to address several need to be taken into account in the search for automation and optimization of coverage route planning for BC using UAVs, such as: identifying the main characteristics of the coverage area, looking for suitable landing and take-off points, determining the distance between the parallel line of the coverage trajectory due to the biological agent in use, setting the flight altitude, safely returning to the base, and generating ready-to-fly route coverage files. This article presents a framework and implementation containing a coverage path planning algorithm for automating biological control routes considering essential aspects of a real-world scenario. Actual flights using the framework implementation show the efficiency and reliability of the proposed approach.**

***Index Terms*—Biological control, UAV, Route planning, Coverage Path Planning**

I. INTRODUCTION

As reported by the Food and Agriculture Organization of the United Nations (FAO) [1], it is estimated that 20 to 40% of the world's agricultural production is lost each year due to pests that affect crops, a value corresponding to approximately 220 billion dollars. In Brazil, it is estimated that losses reach 55 million dollars. To reduce loss, Biological Control (BC) methods, which use natural enemies (parasitoids, predators or pathogens), have become an alternative for pest control in crops, or in a complementary way to chemicals, in order to reduce impacts and costs. According to [2], BC is a rational and healthy method that does not leave sediment in food and is harmless to the environment and the population's health.

Depending on the pest, it can infect the entire crop. Then, reductions in inoculum require continuous dedication and workforce resources. The cost of management can include inspections carried out by specialists and the application of insecticides, which can increase production costs [3].

The major challenge is finding an efficient and economically sustainable way to distribute biological agents in agricultural areas. An interesting alternative would be the proposition of intelligent mission planning using Unmanned Aerial Vehicles (UAVs) to transport and spread these agents. For [4], the use of a UAV is a promising BC platform, as it can reduce costs and overcome natural barriers, such as rivers or contact with dangerous wildlife (e.g., snakes and spiders), with high efficiency and a wide application range.

The UAV must fly over a particular area, including all locations, to transport and spread the biological agents. This problem is a subtopic of Robotics known as Coverage Path Planning (CPP) [5]. In addition to planning the trajectory, it is necessary to identify the most suitable take-off and landing positions, viable for the human operator to accomplish either autonomous or non-autonomous missions. Many factors can influence the decision of the take-off and landing positions, which can vary and be updated when the UAV operator arrives in such an area due to erosion or flooding on the unfrequented or inspected roads of large farms.

Moreover, safety issues must also be considered concerning the energy available in the vehicle's batteries. Vehicles must return to base before their energy source is completely depleted to avoid collisions and accidents. The larger the coverage area, the longer the time spent manually planning routes. Considering extensive areas, it is also necessary to divide them into sub-areas to carry out multiple flights. All these issues are significant constraints to be considered in the CPP problem in a real scenario.

This paper proposes a framework for aerial coverage plan-

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ning missions using UAVs. The framework consists in managing several missions, organizing them, and providing coverage path planning. To verify our framework proposal, we materialized it into a system. We present an intuitive and friendly interface for area definition using a map, a configuration system to determine UAV parameters (speed, altitude, and distance), an automated BF algorithm for coverage over crop fields with take-off and landing spots chosen by the user, and a tool to save ready-to-fly waypoints files.

The following sections of this article are organized as follows: Section II presents a background contextualization. Section III discusses work related to smart solutions for BC exploring the CPP problem. Section IV presents the framework for route management for BC. Section V presents the framework implementation as a JS-based web application that aims to optimize the transport and dispersion of biological agents in crop fields. Section VI further explains the proposed algorithm for the CPP problem. Section VII shows the actual flight experiments performed to validate the proposed approach; and finally, Section VIII draws conclusions and future work.

II. BACKGROUND CONTEXTUALIZATION

Brazil is a world leader in agribusiness. However, this title is associated with the high use of synthetic pesticides. According to the Brazilian Institute of Geography and Statistics (IBGE), the use of pesticides to control pests, diseases, and weeds have more than doubled in ten years. From 2002 to 2012, the sale of pesticides in the country increased from about 3kg per hectare to 7kg. The IBGE also evaluates the different types of pesticides sprayed on crops. About 30% of pesticides were classified as highly hazardous [2].

Despite this alarming and worrying data, Brazil began to stand out positively in BC. With application in more than 23 million hectares, it is the world leader in BC and already exports technologies to other countries. While the global market for biological agents grows by 9%, indicators show that Brazil recorded an increase of more than 15% in 2020 [6]. The growing use of BC is also due to people seeking healthier foods produced in a sustainable way and with no contamination the environment. Another factor that justifies the growth is the resistance developed by pests to available chemicals, which are no longer as effective.

Although it is a sustainable alternative in a promising market, BC still lacks means of transportation and dispersion of natural enemies to be carried out in a more intelligent and effective way. Some initiatives explore the use of UAVs with onboard dispensers. These devices can store and disperse natural enemies at regular intervals of time. Typically, these vehicles are guided by remote control or have a flight plan stored in their memory, previously made manually through a Ground Control Station. The Mission Planner is one of the most popular open-source flight planning software. Its interface is only compatible with the Windows system. Some of the initiatives that use UAVs for BC to explore the CPP problem are detailed in Section III, followed by the solution proposed in this study.

III. RELATED WORKS

Energy-aware CPP solutions for UAVs were recently proposed by [7] and [5]. In the work of [7], a coverage algorithm based on back-and-forth (BF) motion is proposed for photogrammetry applications, which consists of taking a sequence of aerial photos to assemble a mosaic that can be used in Precision Agriculture for the identification of pests and diseases. Also focused on the photogrammetry, [5] explores the spiral movement to perform a UAV coverage, showing better results in terms of energy consumption compared to its predecessor. Both solutions deal with regular coverage areas (rectangles and simple polygons), but do not consider the transport and dispersion of biological agents.

The work of [8] proposes a solution for the CPP for the formation of mosaics in Precision Agriculture, dealing with more complex and irregular areas that may contain no-fly-zones. The research of [9] explores coverage planning using multiple UAVs with varying characteristics in wider irregular areas. In the referred work, the area is divided into subareas and assigned to each UAV. The vehicles explore their respective sub-areas individually, without any type of communication or coordination between them. The work requires the adoption of a safety boundary between the sub-areas, where vehicles are prohibited from flying over, to avoid collisions between them. Another work, such as [10], describe path planning for multiple UAVs for 2D reconstruction of flat terrains from a fixed altitude. Despite dealing with more complex areas and adopting multiple vehicles, these three approaches also do not explore the transport and dispersion of biological agents.

In the search for patents through the portal of the National Institute of Intellectual Property (INPI) some propositions were found, but most of them are still without concession. The work of [11] proposes a land vehicle containing a dispersion device that moves in lines over the soil of the crop, with the biological units being triggered individually in a timed manner. Another solution is proposed in [12] and [13], where the authors created a multipurpose embedded system to control the process of releasing different biological agents for BC automation by conventional means (e.g. walking equipped with backpacks), land vehicles (e.g. motorcycles, tractors, etc.), manned aircraft (e.g. small agricultural and experimental aircraft) and unmanned aircraft (e.g. UAV). Despite the device being controlled by a standard communication interface of navigation systems and having the option of connecting to a human-computer interface, the proposal does not present innovation in relation to mission planning with UAV integrated with the use of dispensers.

In [14] a system and method are proposed for releasing solid products, in bulk or wrapped, for pest BC using a dispenser coupled to the UAV. However, the UAV is remotely piloted by a human operator. The work of [15] also proposes a dispenser attachable to a UAV, to release the pulp of the biological agent *Cotésia flavipes*, a natural enemy of the stem worm, a pest of plants of the *Poaceae* family, mainly sugarcane. However, this is another proposal that focuses on the creation of the

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dispersion device, without presenting innovation in relation to the manual use of the UAV as a means of transport.

The research by [16] used fixed and rotary wing UAVs, and a base station to map out an action plan for the BC. However, the proposal does not present innovation in the CPP problem, since the flight plan and the choice of the place of deposition of natural enemies are carried out manually, which requires specialized labor, which, in turn, can increase the time and cost of the mission.

In [4] a route optimization for the UAV to launch capsules containing *Trichogramma* was proposed by combining different CPP algorithms. The capsule release locations were calculated using a hexagon as the base geometry. The route of the UAV should coincide with the center of the hexagon. However, the work does not consider the energy capacity of the vehicle and in areas that require many turning maneuvers, this can result in flight speed instability and increased energy consumption. These aspects are essential for the safe return of the vehicle to base.

In the work of [17] an intelligent dispersal system for *Trichogramma* capsules was developed. It was assumed that effective coverage of a capsule is defined as a circular area. The capsule release route and interval is determined by the capsule coverage radius. The flight plan uses the BeiDou positioning system, with BF flight pattern. The experiment does not deal with the problems of safely returning from the area to base and does not explore complex coverage areas.

Most of the proposals are directly related to the technology for creating intelligent dispersion devices, without presenting an intelligent solution integrated with UAVs to optimize mission planning in order to expand the coverage area of these vehicles. In our case study, we already have the device for scattering, and we will deal with the mission planning problem. In addition, the solutions found do not explore the potential for optimizing coverage in order to build an effective and safe mission plan that expands the area of operation of the air vehicle.

IV. THE FRAMEWORK

To manage missions, organize them and provide better CPP for the UAV, the sequential steps of the proposed structure are summarized in the Fig. 1.

It follows bellow is an explanation of each step:

(A) Delimitation of the Coverage Area, locating in a satellite image (map) the area for pest control, and drawing a polygon on the map, usually defined by an expert.

(B) Set Mission Parameters, speed, altitude, and distance between lines of the coverage path that will be carried out by UAV. These parameters are related to BC in a real scenario;

(C) Takeoff and Landing Waypoint, defined arbitrarily by the human operator, assigned to any vertex of the polygon drawn in step (A);

(D) Coverage Path Planning, generated automatically from data from previous steps. The algorithm dynamically generates routes with the BF pattern from the waypoint defined in (C), and calculates the estimated time of flight based on the speed and distance to be covered by the UAV;

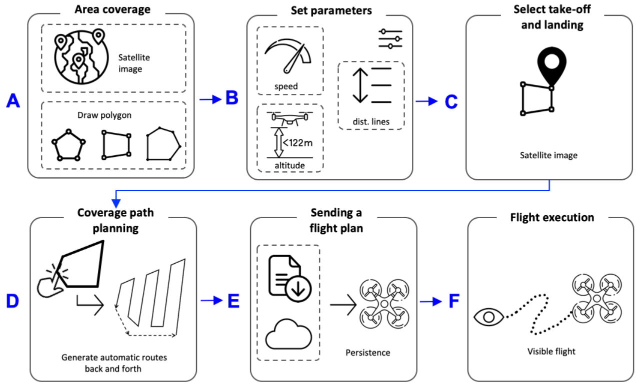

Fig. 1: Framework propose

(E) Sending a Flight Plan to the aircraft. A waypoint sequence file can be generated, stored in a data persistence device, or sent directly to the UAV. Data persistence is necessary for possible adjustments to the flight plan in the real scenario, bringing restrictions that were not identified in step (A);

(F) Flight Execution for the application of biological agents by the UAV.

Fig. 1 shows the activities for optimizing the automation of the CPP related to BC by UAV. Steps (A), (B) and (C) are user inputs; (D) designs the coverage route in a fast, friendly and dynamic way, according to step (C); Steps (E) and (F) are outputs that allow the management and execution of the CPP. Below we describe how the framework was implemented.

V. FRAMEWORK IMPLEMENTATION

In order to verify the proposed use of CPP techniques in confirmed cases of BC use, the framework was materialized as a system. A system that can be used in the field where farms in Brazil have two main limitations: (1) the absence of internet connectivity during an application that may require an adaptation of the flight plan in loco; (2) the need for using low-end computers or tablets that would hardly have the high processing capacity to process optimization tasks.

The system is a JS-based web application which explores the Mapbox GL JS (mapbox.com) and the Turf.js Library (turfjs.org). The coverage area is defined by drawing a polygon through a friendly and intuitive application interface. Next, the take-off and landing position is selected by clicking on one of the vertices of the area and the proposed algorithm generates the coverage path. The trajectory consists of BF movements aligned parallel with the major edge, which guarantees performance optimization considering time flight as a metric.

A. Coverage Area Delimitation

The system presents a satellite map interface with the message "Draw a polygon" in the central/upper part of the screen and a search form field to select a specific location to redirect the map in the upper/right corner. Control buttons to

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zoom in and zoom out are available bellow the search field, as well as the draw polygon button and the trash can button.

The user can select the draw polygon button and determine the crop area by clicking directly in the map. Every click on the map represents a vertex of the polygonal area. Double click in the last vertex finishes the draw of the polygon. The dashed orange line represents the crop area to be covered by the UAV. Once the polygonal area is finished, it is possible to select and erase specific vertices using the trash can button. Fig. 2 presents the application interface.

24.56 ha | 5.31 Km | 11m03s

Plantation

☑ WP Grid

Altitude: 10m

Speed: 8m/s

Distance: 50m

Fig. 2: Application Interface for CPP with UAV

B. Mission Parameters Configuration

The system contains three mission parameters: altitude, speed, and distance. The altitude parameter sets the distance between the UAV and the ground, and its value varies from 10m to 50m. The speed parameter configures the UAV flight speed to perform the coverage, varying from 1m/s to 15m/s. Finally, the distance parameter represents the distance between the parallel lines of the BF movement, and its value can vary from 1m to 100m.

The user should previously configure the parameters according to the type of mission using the blue button in the lower/right corner. However, the application is flexible and it is also possible to change the parameters after the path generation. In this case, the coverage path is re-rendered according to the new values. The application also allows the user to select a type of plantation with pre-defined values for the parameters. Furthermore, there is a "WP Grid" option for generating Intermediate Waypoints (IW) across the path. The distance between the IW is the same as the distance between the lines. The IW can be used to activate a specific command in the flight controller, such as open or close a dispenser to spread biological agents.

C. Take-off and Landing Localization

The take-off and landing position is setup by selecting one of the polygon vertices. Fig. 2 presents the selected vertex highlighted by the the larger orange circle in the upper/right corner of the area. This step is still manually performed by the user considering the knowledge about the crop field and its surroundings, such as roads, lakes, and inaccessible places.

The coverage path consists of three phases illustrated by different colors. The blue color is the initial phase, where the UAV moves from the take-off position to the beginning of the back-and-forth (BF) movement. The yellow color represents the intermediate phase composed by BF movements aligned to the longest edge of the polygon. This strategy reduces the coverage time, which is directly related to the minimum number of turning maneuvers. Finally, the final phase is represented by the green color and indicates the sub-path that connects the end of the BF and the landing spot. The coverage path parts near the external limits of the area are not placed over the edges, but positioned considering half of the distance between the lines to improve the coverage performance.

D. Dynamic Area, Distance, and Time Data

Coverage data is available in the upper/central part of the map. The data is dynamically updated as the crop area and the coverage path are generated or modified by the user's interaction with the application. Fig. 2 presents data related to the size of the area (24.56 ha), total length of the path (5.31 Km), and flight time (11m03s). It is possible to increase or reduce the distance parameter leading to an increase or reduction in the number of BF parallel lines. This modification also changes the total length of the path and the flight time to perform the coverage.

E. Save and Import Files

The mission button (green color) located on the lower/left corner presents the several options. The "New" option resets the parameters and clean the map. The "Save" option stores a file in *.txt* format with all waypoints and area coordinates. The file is compatible with most of the flight controllers on the market and contains commands such as take-off (code 22), change speed (code 178), and move to waypoint (code 16). The file also contains information on latitude, longitude, altitude, and speed. The "Open" option selects and opens a previously saved file, allowing modifications in the original area and path.

The option "Import Point" opens a *.kml* file and redirects the map to the location, while the "Import Poly" draws a polygon according to existing coordinates. It is possible to edit the polygon by right double-clicking and dragging the vertices, and also delete vertices in the trash can button.

VI. ALGORITHM IMPLEMENTATION

One of the main advantages of this framework proposal is that it can be used in low-end equipment, even smartphones. For this reason, a polynomial order algorithm is proposed instead of using optimization techniques. This section presents an algorithm with time complexity $O(n^2)$, where n is the number of vertices of the polygon. For the same reason, we present an implementation that is agnostic and can be run on different platforms. Algorithm 1 presents the BF Algorithm for BC.

The algorithm input consists of a polygon represented by a set of vertices $\{v_1, v_2, ..., v_n\}$ and the starting/final position defined by P_{start}, indicating the take-off and the landing

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Algorithm 1 Back-and-Forth Algorithm for BC

```
Input: A set of vertices ${v_1, ...v_p}$ and the starting position $P_{start}$
Output: A set of waypoints ${w_1, ...w_p}$
 1: Compute the longest edge $L_{edge}$ of the polygon
 2: Compute the angle $\alpha$ of $L_{edge}$
 3: Create a bounding box $b_{box}$ around the polygon
 4: Draw parallel lines $pl$ inside the $b_{box}$
 5: Rotate the $pl$ according to the angle $\alpha$ of $L_{edge}$
 6: for $i = 1$ to $pl$ do
 7:     for $j = 1$ to $v_p$ do
 8:         Compute the intersection points $i_p$ of $pl$ for every $v_j$
 9:     end for
10: end for
11: for $i = 1$ to $i_p$ do
12:     $d_{indent}$ = half of the distance between the lines
13:     $p^i_{bf}$ = Add $d_{indent}$ to the coordinates of $i^{ith}_p$
14:     $p^{i+1}_{bf}$ = Add $d_{indent}$ to the coordinates of $i^{ith+1}_p$
15:     $line$ = create a line with $p^i_{bf}$ and $p^{i+1}_{bf}$
16:     if $line$ is EVEN then
17:         Invert the coordinates of $p^i_{bf}$ and $p^{i+1}_{bf}$
18:     end if
19: end for
20: $fp$ = first point of $i_p$
21: $lp$ = last point of $i_p$
22: Generate the sub-path $p_{initial}$ from the $P_{start}$ to the $fp$
23: Generate the sub-path $p_{final}$ from the $lp$ to the $P_{start}$
24: Combine $p_{initial}$, $p_{bf}$ and $p_{final}$ to generate the full
    coverage path
```

location for the mission. Each polygon vertex is represented by two values: latitude and longitude. The first step of the algorithm is to compute the longest edge L_{edge} of the polygon and its angle α considering the coordinates of the area. The distance between two consecutive vertices is measured and the process is repeated until all vertices are explored. Aligning the BF movement according to the angle of the longest edge is important because it improves the performance of the coverage mission by reducing the number of turning maneuvers and, consequently, reducing the flight time.

Then on the line 3, the algorithm draws a bounding box b_{box} around the polygon and generates parallel lines pl inside the bounding box (line 4). These parallel lines are separated from each other according to the distance parameter. This parameter sets the distance between the lines. The parallel lines are rotated according to the angle α of the line formed by the L_{edge}, as shown on the line 5.

Then, between lines 6 and 10, we explore all vertices of the polygon and all parallel lines to discover the intersection points i_p between them. After, we modify all i_p (lines 11 to 19) by adding an indent that is half of the distance between the lines. This is necessary to avoid the turning maneuvers of each line segment over the limits of the polygonal area, maintaining the path inside the delimited crop field. Every two intersection points form a segment line (line 15). If the line is even, the coordinates of the points are inverted to create the BF pattern (line 17).

Finally, we compute the sub-paths of phase 01 and phase 03 on lines 22 and 23, respectively. The sub-path $p_{initial}$ consists of a path from the starting point P_{start} to the first point (intersection point) f_p of the BF movement, passing by all intermediate vertices between the two points. This sub-path also presents an indent from the limits of the polygon, avoiding passing over the edges. The sub-path p_{final} consists of a path from the last point l_p of the BF movement to the P_{start}. At the end of the algorithm, we combine the three phases to generate the full coverage path, exporting a file containing a set of waypoints $\{w_1, w_2, ..., w_p\}$.

VII. EXPERIMENTS AND RESULTS

After verifying the executability of the proposed framework that was carried out through its implementation in the previous section, tests were carried out for its validation. For this, flight plans and actual flights were performed over a crop field using a UAV containing a dispenser attached to its frame to validate the application and analyze the framework. The UAV model in use is a custom made multirotor with four motors (a quadcopter) with an AUW of approximately 1.9kg. The UAV has four 140W motors, 9-inch propellers, and a 5000mAh four-cell battery (14.8V). The flight time of the UAV is a minimum of 20 minutes. The usual flight speed is 10m/s and can reach 15m/s if necessary. The equipment is similar to the DJI Phantom 4.

The UAV characteristics make it possible to cover an area of up to 30 hectares, although flight plans usually do not exceed 20 hectares. The control of the UAV itself relies on the Ardupilot stack compatible flight controller board. Table I presents the results obtained in regular rectangles areas. The idea is to compare the automated path generated by the algorithm with the best case scenario for humans, which is manually planned paths in simple areas. More complicated areas would consume more time for humans to plan it, but would make no difference in the algorithm's computational time. These areas are approximately 25ha. The distance between lines for BC was 30 meters(m), and the UAV speed was 10m/s.

TABLE I: Experiments results

Comparison	**Manual path planning**	**Framework usage**
Flight plan confection	from ω(5min)	up to $O(10seg)$
Change of polygon vertex position	from ω(1min)	up to $O(5seg)$
Change of take-off/lading location	from ω(5min)	up to $O(1seg)$
Flight time	around 15min	around 19min
Spacing between lines (target 30 m)	inaccuracies up to 18%	correctness from ω(99%)

A. Implementation and Usability

For the validation of our approach, the system implemented as presented in Section V was used and compared with flight

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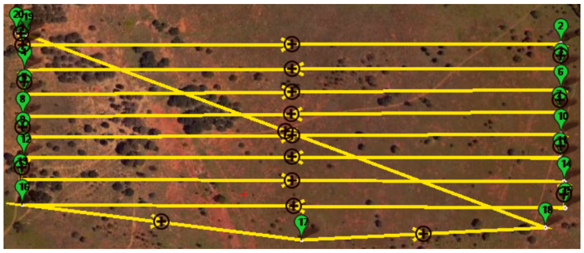
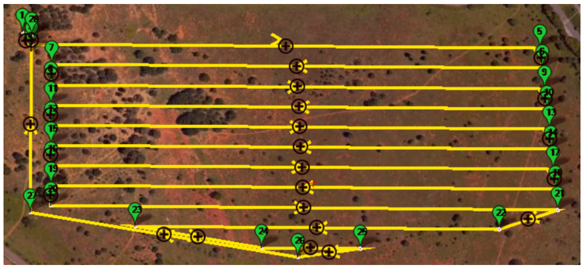


(a) Flight created manually using current tools and work method.



(b) Flight created using the proposed solution.

Fig. 3: Two simple graphs

plans created by professionals with more than five years of experience, specifically in the use of UAVs and management of their routes for BC application. Fig. 3 shows two examples of created flights. Fig. 3a shows a manually created flight using current tools and a working method. Fig. 3b shows a created flight using the proposed solution. Different formats of areas were tested, and the more irregular the areas were, the more significant the difference between the time of making the route by the human operator, as expected.

In Table I, the first three results presented refer to the preparation time or adequacy of a flight plan from the information of the GPS coordinates of the vertices of the areas. As expected, the difference between the times is huge. It is important to emphasize that the polygons involved are simple, and the operator in question has much experienced in the task. Furthermore, we emphasize that the often and simple operation of changing the take-off and landing point requires that a new plan be created.

B. *Effectiveness*

The case study and experiments presented an unexpected result in the fourth line of Table I. The flight time that culminates in battery use is usually shorter in manual plans. However, analyzing the plans presented, it was possible to find a difficulty for operators in fixing the distance between the lines for the application of BC. The last line of Table I shows that at 30-meter spacing, operators tend to move the spacing further apart, causing an average error of 18%. Such error makes the UAV fly for a shorter time and travel the area faster. However, it is not compliant with the BC application. Figure 3 shows two planes over the same area. Although they look very similar, they have flight times and inaccuracies on the magnitude scale presented in Table I.

VIII. CONCLUSION

This work proposed an approach for dispersing BC in crops using UAVs. A detailed technical report of the framework implementation was presented, and its usability was explained. This framework has been implemented and tested. In addition, real flights were conducted to validate the end-to-end approach. Tests showed results supporting that the use of the framework brings much more agility in managing missions. In addition, it was also possible to reduce the average human error of 18%, which, due to automation, can be radically reduced to less than 1% in the distances between the lines necessary for the BC. In future work, we intend to explore the coverage path planning problem in larger areas, investigating different decomposition methods to split the area into subareas to be covered by multiple flights.

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