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Complete coverage path planning using minimum snap trajectory for UAVs in precision agriculture

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ABSTRACT :*The contribution of this work focuses on generating the minimum snap trajectory for a UAV to distribute medicine to all the infected areas of an agricultural environment which contains non-convex obstacles, pest-free areas, and pests-ridden areas. Based on the information on the map regarding the coordinates of the obstacles, non-infected areas, and infected areas, the infected areas are divided into a number of obstacle-free convex polygons. First, the best path which contains waypoints is generated for the UAV such that if the UAV follows that path, it can distribute medicine to the whole area of a convex polygon that contains two parallel edges. However, the UAV is a dynamic system, it cannot perform sharp turns at points. Furthermore, due to the non-zero response time of the controllers, as well as noise factors such as wind, the UAV cannot completely follow the straight lines. Therefore, the next part of the paper focuses on generating the minimum snap trajectory for the UAV with some additional constraints that ensure the coverage of pesticides in all the infected areas of a convex polygon and the whole agricultural area. The algorithm of the proposed method has been tested on MATLAB and can be used in precision agriculture.*

KEYWORDS *Precision agriculture (PA), UAV, Minimum snap trajectory, coverage path planning(CPP).*

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I. INTRODUCTION

Due to limited land resources on the planet and a rapidly growing global population, several serious challenges and problems to humans are climate change, air pollution, sustainable energy, and food production. For the food production problem, crop yields need to be improved within the same agricultural area, and the environmental impacts as well as diseases. For improving the crop yields, we can not only need to create more varieties that can tolerate weather or disease but the crop status should also be monitored more frequently. Information on the pest status, as well as the nutritional status of the crop, will be reviewed by agronomists. They will make decisions on adding nutrients and spraying pesticides for plants in the most reasonable way. Several types of robots used in agriculture have been improved, researched, and built by scientists. Such types of agricultural robots are widely used for obtaining information about crop health, fertilization, or harvestings, such as a mobile robot [1] [2], drone (UAV) [3] [4], or the cooperation of both [5].

Nowadays, quadrotors are increasingly attracting the attention of scientists due to the capability of high maneuverability, low cost. Quadrotor are increasingly expanding to commercial, scientific,entertainment and other applications, such as security andsurveillance, product delivery, aerial photography, especiallyin agriculture.

Quadrotorapplications in agricultural research are becomingmore noticeable in the literature. In [6], the authors evaluatedan aerobatic model plane for high-resolution digital photography used to estimate the nutritional status of corn and cropbiomass of corn, alfalfa, and soybeans.

Quadrotor is widely used in agriculture, especially in crop monitoring, pest detection, pesticide spraying.To detect pests, Quadrotor is usually equipped with a special camera, ultrasound or thermal imaging carried on board to detect abnormal levels of radiation in the infrared spectrum emitted by plants.By analyzing the gathered images and spectral, ones can detect the area of infected plants and their position in the agricultural area.After that, we need to generate a trajectory for the quadrotor to come and spray pesticides on all the affected crop areas.This trajectory must meet a number of properties, such as, (i) ensuring that robots will monitor or spray the entire area of the plant to be monitored while avoiding obstacles, (ii) optimizing the area to be monitored, and/or (iii) optimize the travel distance or working time of the robot.

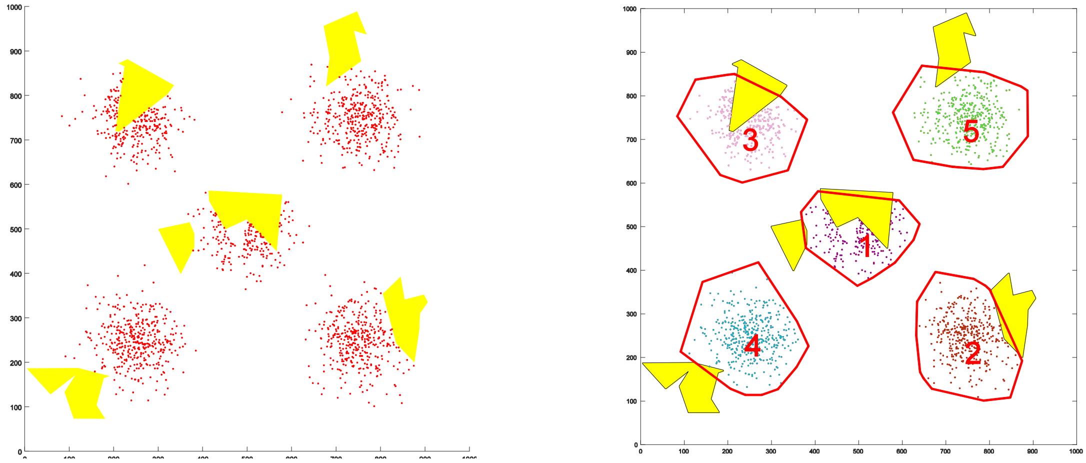
One of the most important tasks for robot movement is Coverage path planning (CPP). CPP is the identification of a trajectory that a robot must follow to pass each point in an environment while avoiding obstacles. Based on the generated trajectory, the robot can accomplish pre-defined tasks. For generating trajectory for the robots, first, the environment needs to be divided into smaller obstacle-free regions, then the trajectory in each region has to be generated. CPP has been extensively studied in recent years for applications such as vacuum cleaning robots [7], painter robots [8], path planning for autonomous underwater vehicles [9], demining robots [10], lawn mowers [11].

The purpose of this study is to generate the minimum snap trajectory for a quadrotor that sprays pesticides on all infected agricultural areas with non-convex obstacles.

The remainder of this paper is organized as follows. In section II, we analyze the problem by reviewing the results of the previous paper [16] by the author. Thereby giving the necessary improvements to be addressed in this paper.In Section III, the system model is introduced. Section IV is for generating the pathway which contains the way-points for the quadrotor to follow.Then, the minimum snap trajectory for the quadrotor to cover entire the infected areas is generated in section V. Simulation is also given in this section. The section VI concludes the paper and gives some suggestions for future works.

II. PROBLEM STATEMENT

In the previous paper of the author [1], suppose that the agricultural area of interestis as depicted in Fig. 1a. In this figure, there are obstacles (the yellow areas), uninfected plants (the white areas), and infectedplants (the dotted red area). One can see that the infectedarea are close to some obstacles and an UAV which wants tomove from one area to another will meet an obstacle on itspath.



(a). Problem definition (b). Minimal convex polygon covers the infected points

Figure 1: Polygon covers the infected points

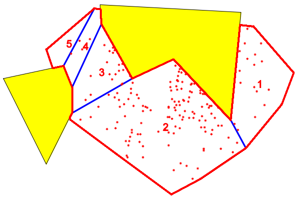
Then, from the data of the coordinates ofthe pests, the infected areas are devided into non-intersecting regions by using clustering algorithms. In Fig.1b, we can see that the infected plants are now devided into several point groups which are called clusters. After that, polygons that containsall the infected points of each generated cluster are generated. two approaches are proposed: (i) find the minimal convex polygon whichcovers all the infected points in each cluster (Fig. 2a), and (ii) find theboundary polygon which covers all the infected points in eachcluster (Fig. 2b).

(a). Boundary polygon covers the infected points (b). Minimal convex polygon covers the infected points

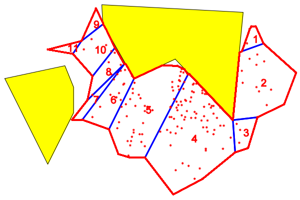
Figure 2: Polygon covers the infected points

After that, each cluster is dividedagain to several obstacle-free convex polygons as shown in Fig. 3a and Fig 3b by using the algorithm that find the .

A convex partition by segments of a polygon is a decomposition into convex polygons obtained by introducing arbitrarysegments [12] [13] [14] [15]. By applying Greene's dynamicprogramming algorithm [12], the polygons as in Fig. 2a and Fig. 2b can bedivided into a minimum number of convex polygons Fig. 3a and Fig. 3b.



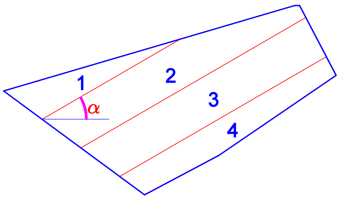
(a). Obstacle-free polygon from minimal convex polygon covers the infected points



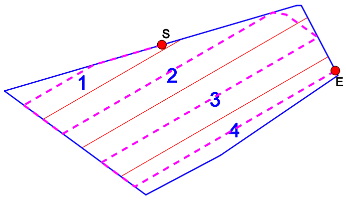
(b). Obstacle-free polygon from boundary polygon covers the infected points

Figure 3: Split convex polygon into several trapezoids

We can see that the convex polygons created in the previous step as shown in Figures 3.a and 3.b are obstacle-free convex polygons. Therefore, if the UAV moves in it, it will not collide with the obstacle. The author of this paper subdivided these convex polygons into polygons $ABCDEFG$ with two parallel sides by finding the appropriate angle α as shown in Fig. 4a and try to find the path that if the UAV moves along that path, whole area of the polygon can be covered by medicine as in Fig. 4b.



(a). Split convex polygon into several trapezoids with α angle



(b). Path way with α angle

Figure 4: Split convex polygon into several trapezoids

The path for the UAV to follow in each convex polygon $ABCDEFG$ with two parallel sides in Fig.6 is NMP.

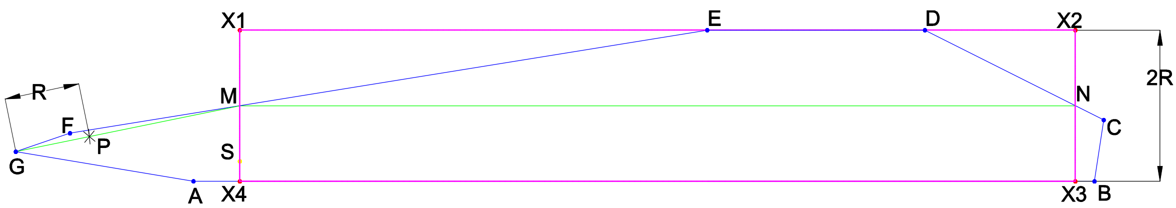


Figure 5: Trapezoid

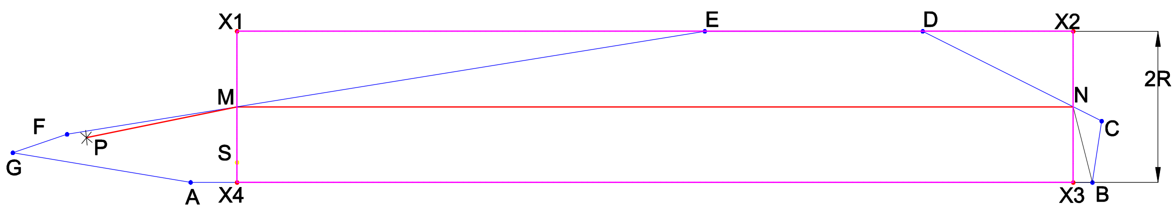


Figure 6: Way-points of trapezoid

However the trajectory generated as in [12] has some following drawbacks:

- The UAV is a dynamic system, it cannot perform sharp turns at points. Furthermore, due to the non-zero response time of the controllers, as well as noise factors such as wind, the UAV cannot completely follow the straight lines. Consequently, the UAV can not completely follow the path from M to N and to P.

- Points M and N are on the borderline of the polygon $ABCDEFG$

This paper extends the results of the paper [1] with the assumption that the UAV controller works such that when driving the UAV to a given position, the position deviation is not more than a given distance r and the trajectory is smooth enough for the UAV to follow.

III. SYSTEM MODEL

This study deals with UAVs that are equipped with a mechanism that can spray the crop. The distance from theUAV to the fixed plant under h and a radial area of radius $R+r$ (Fig. 7) of the crop below the UAV can be covered by the pesticide. We also consider that the UAV always

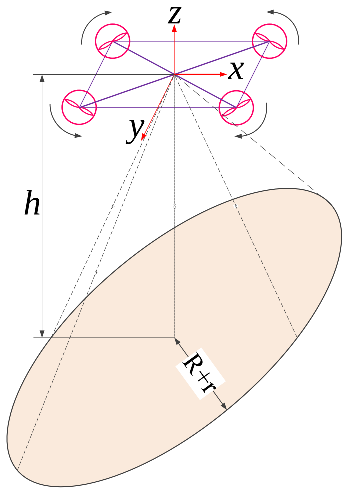


Fig. 7.UAV with frame picture capture

IV. PATH GENERATION

Consider the convex polygon $ABCDEFG$ with two sides AB and DE are parallel to each other and separated by adistance of 2R as shown (in Fig. 8). In this section, we are only interested in creating a motion path for the UAV with the insecticide spray mechanism as in section III of the trapezoid convex polygon $ABCDEFG$, such that the path lies completely within the polygon and when the UAV moving on this trajectory, the entire area of this polygon will be covered.

Draw a parallel line atdistance R to the edge AB. This line intersects the sides of theconvex polygon ABCDEFG at $H_1 \in CD$ and $H_2 \in \mathrm{EF}$. Next, draw two parallel lines on either side of the line segment H_1H_2 and at a distance r from H_1H_2. Then, construct the smallest rectangle whose sides lie on two parallel lines just drawn and whose two vertices lie on the edge of the polygon ABCDEFG. In this case, it's a rectangle $K_1K_2K_3K_4$. N and P are the intersection of line segment H_1H_2 and the sides of rectangle $K_1K_2K_3K_4$.

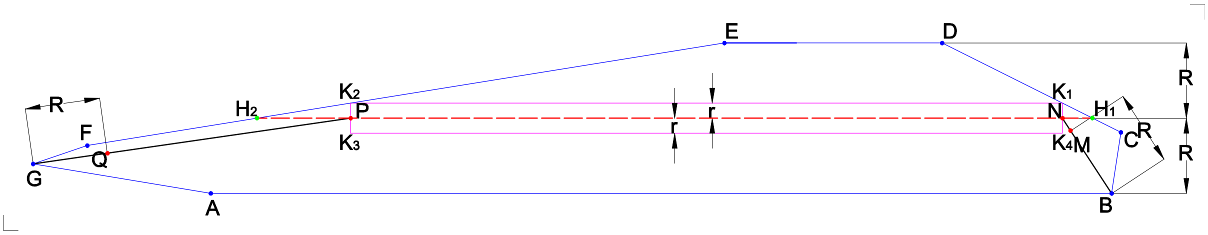


Fig. 8.Trapezoid

For the left side of Fig. 8, find the furthest point from P in the set of points of the convex polygon $ABCDEFG$ to the left of the line K_1K_2. As shown in Fig. 8, it is G. On line segment PG, take a point Q such that $QG = R$.Similarly, with the right side, we determine point M on the line segment NB and is R distance from B.Thus, $MNPQ$ (the red dashed line in Fig. 9) is the shortest path the UAV must follow to cover the entire area of polygon $ABCDEFG$.

However, the UAV cannot completely follow the path $MNPQ$ as discussed in section II. Therefore, we need to create a trajectory for the UAV so that it can still spray pesticides to the entire area of the polygon, satisfying the dynamic characteristics of the UAV, the trajectory is smooth enough and completely inside the polygon for the UAV to follow.

Draw rectangle $I_1I_2I_3I_4$ such that $N \in I_1I_2$, $M \in I_3I_4$, $I_2I_3 \in CD$ and $I_1I_2 = I_3I_4 = 2r$. Then, Draw rectangle $L_1L_2L_3L_4$ such that $P \in L_2L_3$, $Q \in L_1L_4$, $L_1L_2 \in \mathrm{EF}$ and $L_1L_4 = L_2L_3 = 2r$. Thus, it is easy to see that if the UAV moves through points M, N, P, and Q, and the trajectory lies entirely within the rectangles $I_1I_2I_3I_4$, $K_1K_2K_3K_4$, và $L_1L_2L_3L_4$ as the green continuous curve in Fig. 9, then the entire area of the $ABCDEFG$ convex polygon will be covered with pesticides by the UAV configured as in section III. In the next section, we will generate a minimum snap trajectory for the UAV that is smooth enough for the UAV to cover the entire area of the polygon $ABCDEFG$, this trajectory will pass through exactly points M, N, P, and Q, and lies entirely within the rectangles $I_1I_2I_3I_4$, $K_1K_2K_3K_4$, và $L_1L_2L_3L_4$

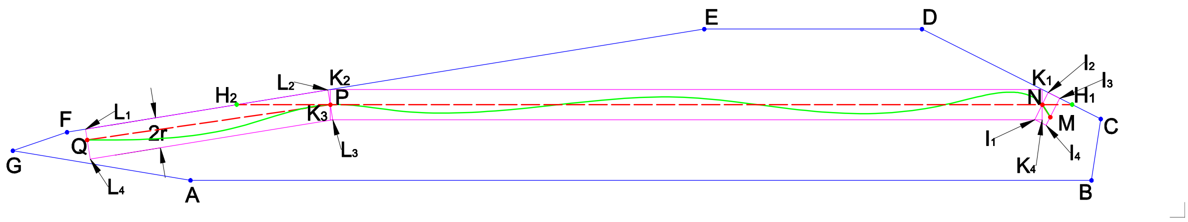


Fig. 9.Way-points generation on Trapezoid

V. MINIMUM SNAP TRAJECTORY GENERATION

A. Minimum snap trajectory for set of points

Given start $P_0\left(x_{P_0}, y_{P_0}\right)$and goal $P_m\left(x_{P_m}, y_{P_m}\right)$positions. We might want the UAV to start from P_0, visit intermediate waypoints $P_1\left(x_{P_1}, y_{P_1}\right), P_2\left(x_{P_2}, y_{P_2}\right), \dots, P_{m-1}\left(x_{P_{m-1}}, y_{P_{m-1}}\right)$ and stop at P_m corresponding at time $t = \begin{bmatrix} t_0 & t_1 & \cdots & t_m \end{bmatrix}^T$ as shown in Fig. 10. Atrivial trajectory that satisfies these constraints is one that interpolates between waypointsusing straight lines. However this trajectory is inefficient because it has infinite curvatureat the waypoints which requires the quadrotor to come to a stop at each waypoint.

In general, we'll insist that the trajectories that the quadrotors follow are smooth because the quadrotor is a dynamical system, it cannot follow arbitrary trajectories. Ourmethod generates an optimal trajectory that smoothly transitions through the waypointsat the given times. This generally translates to minimizing a rate of change of input [17].The optimization program to solve this problem while minimizing theintegral of the fourth derivative of position squared is shown below

$$\begin{aligned}
&\min \int_{t_0}^{t_m} \left[\left(x^{(4)}(t) \right)^2 + \left(y^{(4)}(t) \right)^2 \right] dt \\
&s.t \quad x(t_i) = x_{P_i}, \qquad i = 1, \dots, m \\
&\qquad y(t_i) = y_{P_i}, \qquad i = 1, \dots, m \\
&\qquad \left. \frac{d^j x(t)}{dt^j} \right|_{t=t_i} = 0 \;\; or \;\; free, \;\; i = 0, \dots, m; \;\; j = 1, \dots, 4 \\
&\qquad \left. \frac{d^j y(t)}{dt^j} \right|_{t=t_i} = 0 \;\; or \;\; free, \;\; i = 0, \dots, m; \;\; j = 1, \dots, 4
\end{aligned} \tag{1}$$

Next we write the trajectories as piecewise polynomial functions as in (2)

$$x(t)=\begin{cases} x_1(t), t_0 \le t \le t_1 \\ \cdots \\ x_m(t), t_{m-1} \le t \le t_m \end{cases} \tag{2}$$

$$y(t)=\begin{cases} y_1(t), t_0 \le t \le t_1 \\ \cdots \\ y_m(t), t_{m-1} \le t \le t_m \end{cases} \tag{3}$$

where

$$\begin{cases} x_1(t)=c_{x_{17}}t^7+c_{x_{16}}t^6+c_{x_{15}}t^5+c_{x_{14}}t^4+c_{x_{13}}t^3+c_{x_{12}}t^2+c_{x_{11}}t+c_{x_{10}} \\ \cdots \\ x_m(t)=c_{x_{m7}}t^7+c_{x_{m6}}t^6+c_{x_{m5}}t^5+c_{x_{m4}}t^4+c_{x_{m3}}t^3+c_{x_{m2}}t^2+c_{x_{m1}}t+c_{x_{m0}} \\ y_1(t)=c_{y_{17}}t^7+c_{y_{16}}t^6+c_{y_{15}}t^5+c_{y_{14}}t^4+c_{y_{13}}t^3+c_{y_{12}}t^2+c_{y_{11}}t+c_{y_{10}} \\ \cdots \\ y_m(t)=c_{y_{m7}}t^7+c_{y_{m6}}t^6+c_{y_{m5}}t^5+c_{y_{m4}}t^4+c_{y_{m3}}t^3+c_{y_{m2}}t^2+c_{y_{m1}}t+c_{y_{m0}} \end{cases} \tag{4}$$

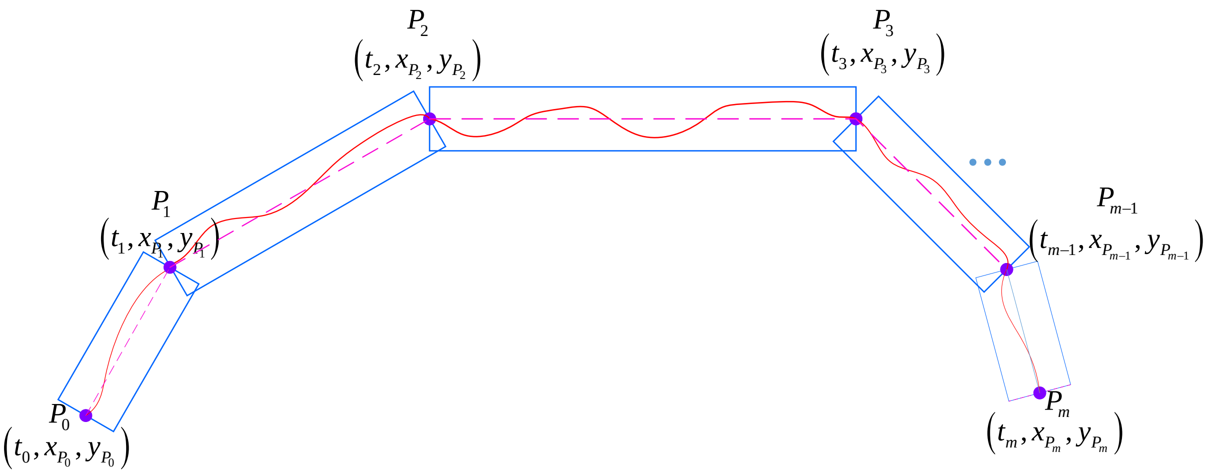


Fig. 10. Way-points for the UAV to follow

The optimization problem now is equivalent to

$$\begin{aligned} &\min\left[\int_0^{t_1}\left[\left(x^{(4)}\right)^2+\left(y^{(4)}\right)^2\right]dt+\cdots+\int_{t_{m-1}}^{t_m}\left[\left(x^{(4)}\right)^2+\left(y^{(4)}\right)^2\right]dt\right] \\ &s.t\quad x(t_i)=x_{P_i},\qquad i=1,\dots,m \\ &\qquad y(t_i)=y_{P_i},\qquad i=1,\dots,m \\ &\qquad \left.\frac{d^j x(t)}{dt^j}\right|_{t=t_i}=0\ \ or\ free,\ \ i=0,\dots,m;\ \ j=1,\dots,4 \\ &\qquad \left.\frac{d^j y(t)}{dt^j}\right|_{t=t_i}=0\ \ or\ free,\ \ i=0,\dots,m;\ \ j=1,\dots,4 \end{aligned} \tag{5}$$

The minimization problem now can be formulateed as a quadratic program (or QP) as follow

$$\min\ \ c_{xy}Hc_{xy}^T+f^Tc_{xy} \tag{6}$$

$$s.t. \quad A_{eq}c_{xy} = b_{eq} \tag{7}$$

$$A_{ieq}c_{xy} = b_{ieq} \tag{8}$$

where equation (7) is the equality constraint, equation(8) is the inequality constraint of the quadratic program, and the decision variable vector $c_{xy} = \left[c_{x_{10}},...,c_{x_{17}},...,c_{x_{m0}},...,c_{x_{m7}},c_{y_{10}},...,c_{y_{17}},...,c_{y_{m0}},...,c_{y_{m7}}\right]^T$

B. Constraints for minimum snap trajectory in a corridor

Suppose we want to generate trajectory $\left(x_i(t), y_i(t)\right)$ for the UAV so that the UAV passes exactly through the points P_i and P_{i+1} and this trajectory is completely inside the rectangle $MHKN$ as in Fig. 11. To ensure that the midpoints of the trajectory $\left(x_i(t), y_i(t)\right)$ lie completely within the rectangle $MHKN$, we subdivide the rectangle by evenly spaced lines. These lines intersect the trajectory $\left(x_i(t), y_i(t)\right)$ at $m-1$ points $P_{i_j}\left(x_{P_{i_j}}, y_{P_{i_j}}\right)$ at specified time $t_{P_{i_j}}$ for $j = 1,..,m-1$ respectively. We also suppose the trajectory $\left(x_i(t), y_i(t)\right)$ are n piecewise functions $\left(x_{i_j}(t), y_{i_j}(t)\right)$ between two point $P_{i_{j-1}}$ and P_{i_j} for $j = 2,..,n$ in the form of (2) and (3) and each of these piecewise functions $poly_{i_j}$ is the pair of polygon as defined in (9)

$$poly_{i_j}: \begin{cases} x_{i_j}(t) = c_{x_{i_7}}t^7 + c_{x_{i_6}}t^6 + c_{x_{i_5}}t^5 + c_{x_{i_4}}t^4 + c_{x_{i_3}}t^3 + c_{x_{i_j2}}t^2 + c_{x_{i_j1}}t + c_{x_{i_0}} \\ y_{i_j}(t) = c_{y_{i_7}}t^7 + c_{y_{i_6}}t^6 + c_{y_{i_5}}t^5 + c_{y_{i_4}}t^4 + c_{y_{i_3}}t^3 + c_{y_{i_2}}t^2 + c_{y_{i_1}}t + c_{y_{i_0}} \end{cases} \tag{9}$$

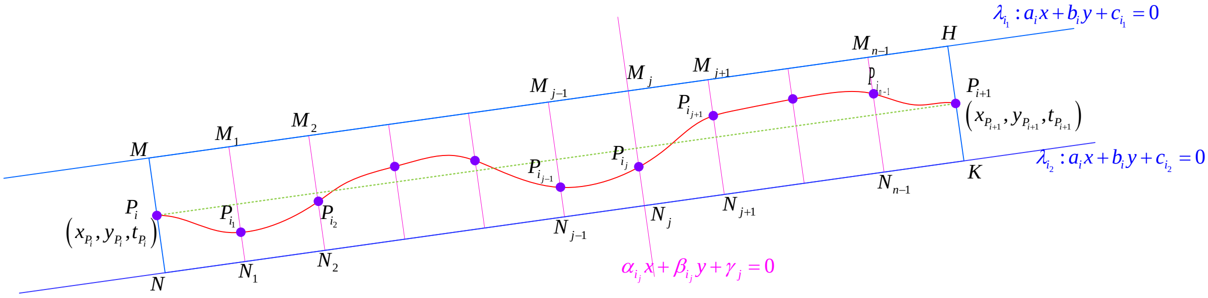


Fig. 11. Minimum snap trajectory inside a corridor

- Equality boundary conditions for initial and final points P_i and P_{i+1}:

$$\begin{aligned} &x_{i_1}\left(t_{P_i}\right) = x_{P_i}; \quad y_{i_1}\left(t_{P_i}\right) = y_{P_i} && x_{i_n}\left(t_{P_{i+1}}\right) = x_{P_{i+1}}; \quad y_{i_n}\left(t_{P_{i+1}}\right) = y_{P_{i+1}} \\ &\dot{x}_{i_1}\left(t_{P_i}\right) = 0; \quad \dot{y}_{i_1}\left(t_{P_i}\right) = 0 && \dot{x}_{i_n}\left(t_{P_{i+1}}\right) = 0; \quad \dot{y}_{i_n}\left(t_{P_{i+1}}\right) = 0 \\ &\ddot{x}_{i_1}\left(t_{P_i}\right) = 0; \quad \ddot{y}_{i_1}\left(t_{P_i}\right) = 0 && \ddot{x}_{i_n}\left(t_{P_{i+1}}\right) = 0; \quad \ddot{y}_{i_n}\left(t_{P_{i+1}}\right) = 0 \\ &x_{i_1}^{(3)}\left(t_{P_i}\right) = 0; \quad y_{i_1}^{(3)}\left(t_{P_i}\right) = 0 && x_{i_n}^{(3)}\left(t_{P_{i+1}}\right) = 0; \quad y_{i_n}^{(3)}\left(t_{P_{i+1}}\right) = 0 \end{aligned} \tag{10}$$

- Equality boundary conditions for middle points P_{i_j}, $j = 1,..,n-1$: at each point P_{i_j} we have to declaire the condition that its coordinates satisfy the equation of $\left(x_{i_j}(t), y_{i_j}(t)\right)$ and $\left(x_{i_{j+1}}(t), y_{i_{j+1}}(t)\right)$ at time $t_{P_{i_1}}$. The conditions are as follows

$$\begin{aligned} & x_{i_1}\left(t_{P_{i_1}}\right)=x_{i_2}\left(t_{P_{i_1}}\right); \qquad y_1\left(t_{P_{i_1}}\right)=y_2\left(t_{P_{i_1}}\right) \\ & x_{i_2}\left(t_{P_{i_2}}\right)=x_{i_3}\left(t_{P_{i_2}}\right); \qquad y_2\left(t_{P_{i_2}}\right)=y_3\left(t_{P_{i_2}}\right) \\ & \dots \\ & x_{i_{n-1}}\left(t_{P_{i_{n-1}}}\right)=x_n\left(t_{P_{i_{n-1}}}\right); \quad y_{i_{n-1}}\left(t_{P_{i_{n-1}}}\right)=y_n\left(t_{P_{i_{n-1}}}\right) \end{aligned} \tag{11}$$

- Equality countinuous conditions for middle points P_{i_j}, $j=1,..,n-1$: with the requirement that the generated trajectories are smooth, the derivative of first order to the derivative of sixth order at point P_{i_j} of $\left(x_{i_j}(t), y_{i_j}(t)\right)$ and $\left(x_{i_{j+1}}(t), y_{i_{j+1}}(t)\right)$ should be equal. The conditions for the derivatives are as follows

$$\begin{aligned} & \dot{x}_{i_j}\left(t_{P_{i_j}}\right)=\dot{x}_{i_{j+1}}\left(t_{P_{i_j}}\right); \qquad \dot{y}_{i_j}\left(t_{P_{i_j}}\right)=\dot{y}_{i_{j+1}}\left(t_{P_{i_j}}\right) \\ & \ddot{x}_{i_j}\left(t_{P_{i_j}}\right)=\ddot{x}_{i_{j+1}}\left(t_{P_{i_j}}\right); \qquad \ddot{y}_{i_j}\left(t_{P_{i_j}}\right)=\ddot{y}_{i_{j+1}}\left(t_{P_{i_j}}\right) \\ & \dots \\ & x_{i_j}^{(6)}\left(t_{P_{i_j}}\right)=x_{i_{j+1}}^{(6)}\left(t_{P_{i_j}}\right); \qquad y_{i_j}^{(6)}\left(t_{P_{i_j}}\right)=y_{i_{j+1}}^{(6)}\left(t_{P_{i_j}}\right) \end{aligned} \tag{12}$$

- Equality conditions for points P_{i_j}, $j=1,..,n-1$ such that P_{i_j} lies in a straight lines with equation $\alpha_{i_j}x+\beta_{i_j}y+\gamma_j=0$ that contains segment M_jN_j

$$\alpha_{i_j}x_{i_j}\left(t_{P_{i_j}}\right)+\beta_{i_j}y_{i_j}\left(t_{P_{i_j}}\right)+\gamma_j=0 \tag{13}$$

- Inequality conditions for points P_{i_j}, $j=1,..,n-1$ such that P_{i_j} lies between two parallel straight lines λ_1 with equation $a_{i_j}x+b_{i_j}y+c_{i_{j1}}=0$, and λ_2 with equation $a_{i_j}x+b_{i_j}y+c_{i_2}=0$ that contain segments MH and NK as shown in Fig.11

$$\begin{aligned} & a_{i_j}x+b_{i_j}y+c_{i_2}<0 \\ & a_{i_j}x+b_{i_j}y+c_{i_2}>0 \end{aligned} \tag{14}$$

C. Simulation result

Write the equality conditions in (10), (11), (12), (13) in the form of equality constraint in (7), and inequality conditions in (14) in the form of inequality in (8) for m segment $P_iP_{i+1}, i=0,...,m-1$ we can formulate the quadratic programing problem on (6). The minimum snap trajectory generated by resolving quadratic programing problem ensure that this trajectory passes through all the waypoints $P_i, i=0,...,m-1$ and lies conpletly in the rectangles as in Fig. 10.

The simulation for a convex polygon is shown in Fig. 12, and the minimum snap trajectory for one part in Fig. 12 is shown in Fig. 13.

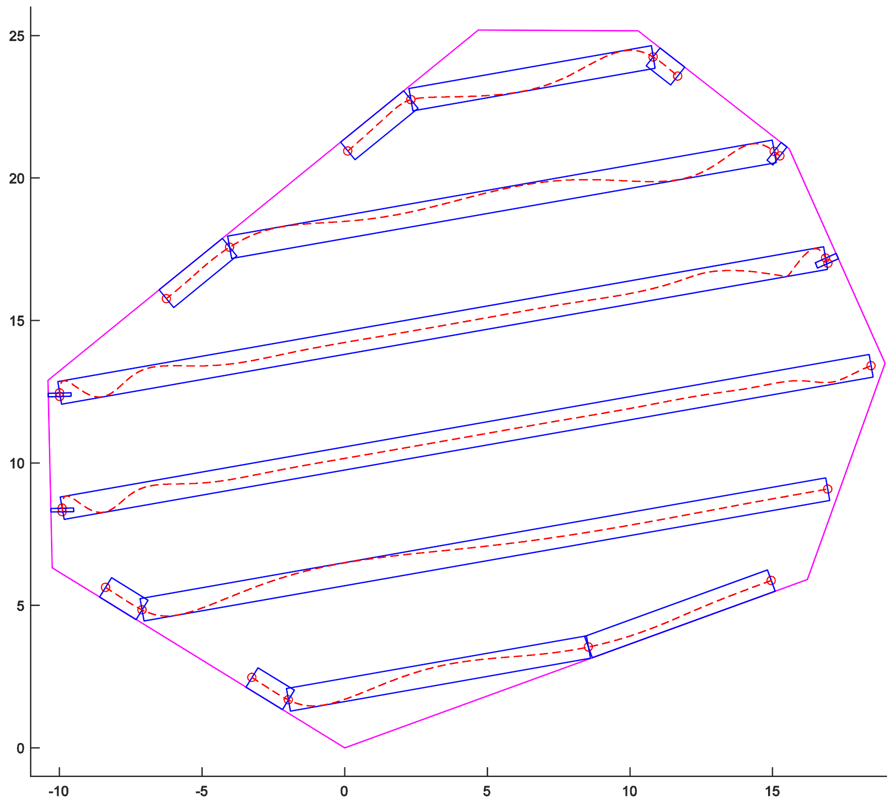


Fig. 12. Complete coverage minimum snap trajectories generation for a convex polygon

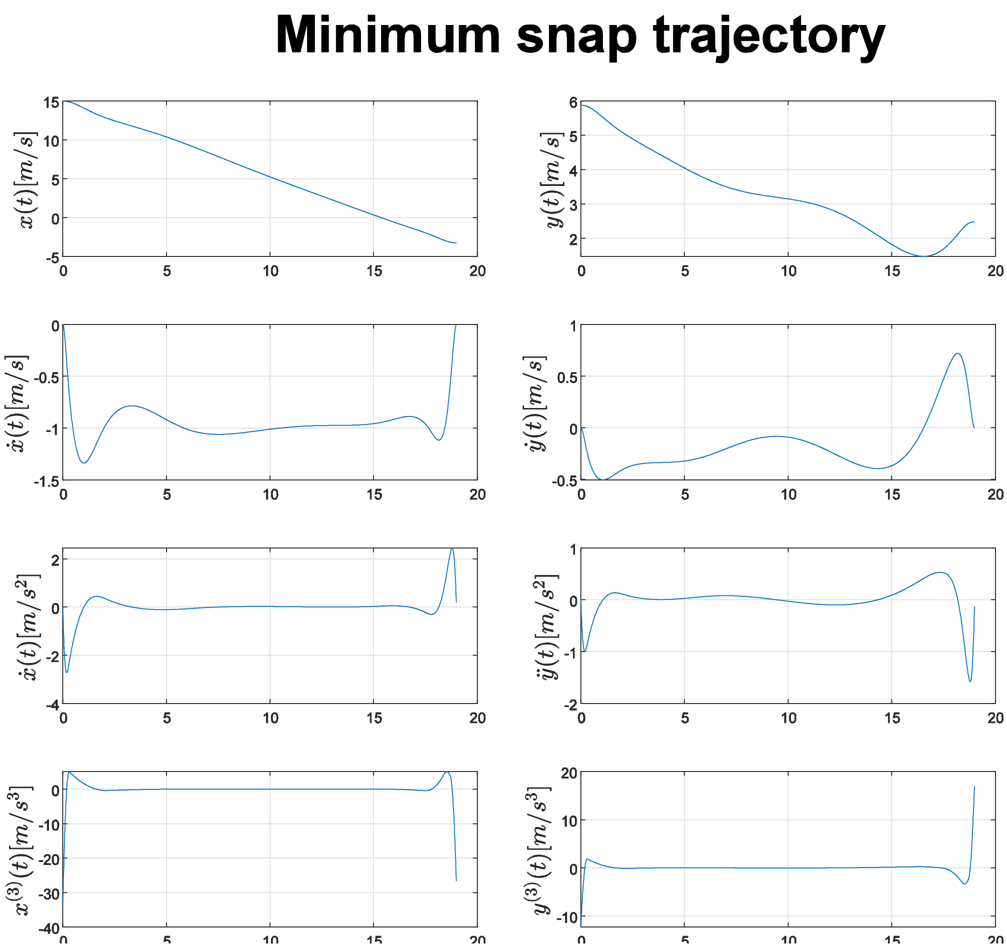


Fig. 13. Minimum snap trajectory

VI. CONCLUSION

In this paper, we have proposed a method for generating aminimum snap trajectory which allows the UAV put the medicine to the entirepest-ridden area of an agricultural area. First, the best path which contains waypoints is generated for the UAV such that if the UAV follows that path, it can distribute medicine to the whole area of a convex polygon that contains two parallel edges. Then, by adding some constraints, the minimum snap trajectory for the UAV ensure the coverage of pesticides in all the infected areas of a convex polygon and the whole agricultural area. This generated minimum snap trajectoryensures that the UAV can follow with limitation of the dynamic and ability of the controller, not colliding with obstacles, and completeness of pesticide coverage in infected areas.

Several extensions from this research are possible. Onemight consider the non-convex shape obstacle, recalculatingthe trajectory under windy condition of the environment, ortrajectory generation for an UAV team. Field tests are alsosubject of future work.

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