Study on Path Planning Algorithms for Unmanned Agricultural Helicopters in Complex Environment

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Abstract

In this paper, two algorithms to solve the path planning problem with constraints from obstacles are presented. One proposed Algorithm is "Grid point-based path planning". The first step of this algorithm is to set points which can be the waypoints around the field. These points can be located inside or outside of the field or the obstacles. Therefore, we should determine whether those points are located in the field or not. Using the equations of boundary lines for a region that we are interested in is an effective approach to handle. The other algorithm is based on the boundary lines of the agricultural field, and the concept of this algorithm is well known as "boustrophedon method". These proposed algorithms are simple but powerful for complex cases since it can generate a plausible path for the complex shape which cannot be represented by using geometrical approaches efficiently and for the case that some obstacles or forbidden regions are located on the field by using a skill of discriminants about set points. As will be presented, this proposed algorithm could exhibit a reasonable accuracy to perform an agricultural mission.

Key Words : Agricultural Helicopters, Path Planning, Autonomous Crop-dusting, Coverage Path Planning

Introduction

Unmanned helicopters have been found ideal for crop dusting owing to their high efficiency in terms of time and pesticide usage. It has been reported that the efficiency from those helicopters is about 100 times higher than the efficiency from manual spraying by farmers.

Another reason to use the unmanned helicopters for automatic crop dusting is on the characteristic environment of Korea. Though almost of fields in Korea are simple such as rectangle or trapezoid nowadays, those fields have very narrow contrast of the fields of the other countries. Although many countries use the unmanned fixed-wing airplanes for crop dusting, it has low efficiency in the case of the field in Korea because a runway for taking off is needed and the speed of vehicles is too fast to cover the narrow fields in Korea. Whereas, if unmanned helicopter can hover or move slowly on the field. It gives a major advantage for this agricultural mission because it is enough to cover the field for crop dusting. In addition, helicopter does not need any runways because it can take off and land on the ground vertically. It is suitable because there are a few runways in Korea.

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However, in order to allow ordinary people without special training to operate highly sophisticated helicopters, majority of operation should be automated, including path planning, and navigation and guidance. Among these, path planning for an agricultural mission such as crop-dusting is an important task due to the optimizing the fuel consumption during the mission and prevention from overlapping the pesticide on a field.

In this paper, two algorithms which can satisfy those conditions introduced above paragraph are presented. One is based on the grid point which can be waypoints under the mission. The other algorithm is based on the boundary lines of the agricultural field, and the concept of this algorithm is well known as "boustrophedon method". These proposed algorithms are simple but powerful for complex cases since it can generate a plausible path for the complex shape which cannot be represented by using geometrical approaches efficiently and for the case that some obstacles or forbidden regions are located on the field by using a skill of discriminants about set points. As will be presented, this proposed algorithm could exhibit a reasonable accuracy to perform an agricultural mission.

To make an adequate algorithm, some condition and rules for crop dusting are required. Those rules are written on the 2nd section. Two proposed algorithms are introduced on the 3rd and 4th sections. The 5th section proposes the multi-agent crop dusting using unmanned helicopters.

Crop-dusting Definition

To make a path planning algorithm, some principles to achieve a mission are required. Since the researches about coverage mission such as automatic lawn mowing or floor cleaning was progressed, the fundamental rules to take a mission are also constructed. Cao, Huang, and Hall defined the criteria for the region filling operation as follows [1]:

1. Robot must move through an entire area.
2. Robot must fill the region without overlapping path
3. Continuous and sequential operation without any repetition of paths is required.
4. Robot must avoid all obstacles.
5. Simple motion trajectories should be used.
6. An optimal path is desired under available conditions.

Because those rules are for the coverage problem, some modification for the agricultural mission by unmanned helicopters is required. In this article, the rules which are defined by Cao at al. are changed as follows:

1. Unmanned Helicopters must move through an entire area without forbidden regions.
2. Unmanned Helicopters must fill the region without overlapping.
3. Continuous and sequential operation without any repetition of path is required.
4. Unmanned Helicopters must avoid all obstacles. Obstacles are defined as the things wh ich are located on the field and have the big height that helicopters cannot pass through the things.
5. The path should be a set of straight lines or circle curves.
6. The path which is solved by the proposed algorithm is admissible.
7. The path for each unmanned helicopter should not be overlapped. If so, the unmanned helicopter should not be collided under the mission.

Path planning for coverage missions is NP-hard, which is hard to know the reasonable solution without considering all of the cases. Therefore, it is also hard to find an efficient algorithm to satisfy those rules written above. Many computer engineers solve that problem

Fig. 1. Characteristics of Agricultural Helicopters

as using the " approximation algorithms" or " heuristic algorithms" , which can give not the perfect solutions but admissible solutions. One approach to get the path planning is to randomize. It is well used in floor cleaning problem, and this algorithm is that when the robot sweeps the floor in random for long enough, it should be cleaned [2]. However, this algorithm can' t be used in agricultural mission because of the rule number 2. Another approach is using the cell decomposition, which is the technique that divides the whole workspace as several simple polygons [3].

The path planning for agricultural missions such as harvesting is being developed nowadays as follows. Sorensen, Bak, and Jorgensen proposed an algorithm by using the Chinese postman problem [4]. Stoll also presented an idea that dividing the field which is treated into subfields based on the longest side of the field or the longest segment of a field polygon [5]. Recently, some algorithms are proposed by using MPC (model predictive control) or neural network approach to optimize the path [6-7].

It is typical NP-hard problem to solve the optimized path for crop-dusting owing to the complexity of fields and non-predictable obstacles. Although the research about this issue is being developed rapidly, the governing algorithm to efficiently find the optimal or reasonable path has not been found yet. The presented algorithms which are introduced on section 3 and 4 do not always give the optimal path, but the result from those two algorithms gives an admissible path.

Fig. 1 shows the characteristics of the agricultural helicopters which are handled in this paper. The covered range to crop dust is R, and it is assumed that those helicopters can hover and level flight under the mission.

Grid Point-based Algorithm

Fundamental Description

This algorithm is based on the gird point which can be the waypoints. The first step of this algorithm is to set those points around the field. All set points satisfy Eqs. (1) ~ (2).

$$P_x = \{x \mid x = \frac{R}{Div} \times i, i \in [-\frac{Grid}{2}, \frac{Grid}{2}]\} \quad (1)$$

$$P_y = \{y \mid y = \frac{R}{Div} \times j, j \in [-\frac{Grid}{2}, \frac{Grid}{2}]\} \quad (2)$$

In those two equations, R is the range of crop-dusting for each helicopter, Div is accuracy. If Div becomes bigger, the cost time becomes also longer. Grid is gotten by Eq. (3).

$$Grid = \frac{\max\{dist(B_i, B_j), i = 1,2...n, j = 1,2...n\} \times 2 \times R}{Div} \quad (3)$$

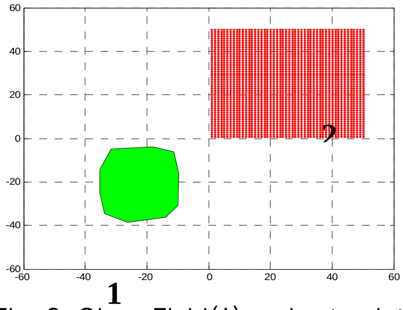

Fig. 2. Given Field(1) and set points(2)

First of all, the handled field can be considered the complex shaped polygon whose boundary consists of some straight lines and there are several vertices which are represented as B_i. Therefore, $Grid$ is represented as the function of distance between set points, and this distance is determined by the accuracy, Div. Because the set region which contains the set points is enough to wide, the number 2 is multiplied on this equation.

The coordinate system of this algorithm is NED (North-East-Down) which is widely used in aerospace field. The origin of this coordinate is the certain point or a landmark which is selected by users.

In this paper, the reference line to arrange those set points is the line which connects set points, and those points can be selected by users in random. This algorithm can generate the admissible result even the 1st and 2nd one are chosen randomly. However, it is better to choose those set points among the points which are near a boundary line to get a possible path. The set points defined by Eqs. (1) ~ (3) should be rotated by the angle between the reference line and x-axis. If this angle is called α, the location of set points is changed by Eq. (4).

$$P_x' = \{x_i \mid x_i = \sqrt{P_{xi} + P_{yi}} \times \cos(\alpha + \tan^{-1}[\frac{P_{yi}}{P_{xi}}])\} \tag{4}$$

$$P_y' = \{y_i \mid y_i = \sqrt{P_{xi} + P_{yi}} \times \sin(\alpha + \tan^{-1}[\frac{P_{yi}}{P_{xi}}])\} \tag{5}$$

Those set points can be located inside or outside of the field. Therefore, a judgment whether a point is inside or outside is required. To do that decision, rotated points should be shifted to make that the center of the field and the center of the set region are on the same point.

$$C_x = \frac{\sum_{i=1}^{m} P_{xi}}{m} - \frac{\sum_{j=1}^{n} BP_{xj}}{n}$$
$$C_y = \frac{\sum_{i=1}^{m} P_{yi}}{m} - \frac{\sum_{j=1}^{n} BP_{yj}}{n} \tag{6}$$

Eqs. (6) shows how much distance to shift from the original region to the field is required. In Eqs. (6), BP_i represents the vertex point of a given field. In this paper, the average value for the vertex with respect to the x and y direction is used to shift. Therefore, the term m on the denominator of those equations means the number of grid points, and the other value n means the number of vertex points on that field. This shift is a kind of calibration, and the fundamental equation of calibration is Eq. (7).

$$\begin{bmatrix} D_{xi} \\ D_{yi} \end{bmatrix} = \begin{bmatrix} P_{xi} \\ P_{yi} \end{bmatrix} - \begin{bmatrix} C_x \\ C_y \end{bmatrix} \tag{7}$$

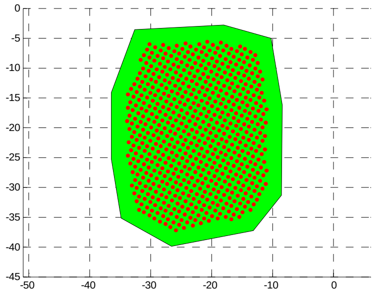

Fig. 3. Result by using discriminants

The matrix which is on the left hand side of Eq.(7) is the coordinate to determine whether that point is in the field or not, and the other equations are needed to determine [8]. If the angle between two edges which share one boundary point is θ, the discriminants are changed by Eqs. (8) ~ (9).

$$\theta_i = \tan^{-1}\left(\frac{BP_{y(i+1)} - BP_{yi}}{BP_{x(i+1)} - BP_{xi}}\right) \tag{8}$$

$$\begin{bmatrix} D_{xj}' \\ D_{yj}' \end{bmatrix} = \begin{bmatrix} \cos(-\theta_i) & -\sin(-\theta_i) \\ \sin(-\theta_i) & \cos(-\theta_i) \end{bmatrix} \begin{bmatrix} D_{xj} \\ D_{yj} \end{bmatrix} = \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix} \begin{bmatrix} D_{xj} \\ D_{yj} \end{bmatrix} \tag{9}$$

In general, if the number of edge for a polygon is n, the number of angle θ is also n. If the sequence of vertex is clockwise direction, which means that the boundary edges enclose the field on clockwise direction. As the section 2 mentioned, the vehicle has a space which range is R. Therefore, to set the configuration space which has a goal that not to spray the outside of the field is required. The final result is,

$$E_x = \{(D_i)_x' \mid (D_i)_x' > -\frac{R}{2}\} \quad . \qquad E_y = \{(D_i)_y' \mid (D_i)_y' > -\frac{R}{2}\} \tag{10}$$

Otherwise,

$$E_x = \{(D_i)_x' \mid (D_i)_x' < \frac{R}{2}\} \quad . \qquad E_y = \{(D_i)_y' \mid (D_i)_y' < \frac{R}{2}\} \tag{11}$$

Fig. 3 shows the result by using those discriminants. To find the real waypoints among those set points, another approach is required. This approach is the other main idea of this algorithm, and it can show the high performance to find a waypoint while the main procedure is simple. Table 1 shows this procedure to find waypoints among the selected set points.

Fig. 4 shows the result by the procedure which is written in Table 1. The result is truly relied on the accuracy value, Div, and the cost time for this algorithm is also determined by that value.

The fundamental pseudo code for this algorithm is written in Table 2. In short, this algorithm considers all of the cases as using set points which is located on the entire region of the field, and finds the real waypoints among the set points. This algorithm is simple but powerful if there are some obstacles on the field. The main procedure for this situation is written on the next subsection. However, if the field has any convex corners, this algorithm shows the critical problem so that some modifications are required. The generalized procedure of this algorithm is also written on the next subsection.

Table 1. Main procedure to find waypoints

Step 1	Set the first waypoint and the direction of a helicopter to proceed for crop dusting. The iteration number, i starts from 2. Go to Step 3.
Step 2	Set the direction of a helicopter as Eq. (12). $$\frac{(WP_{i-1})_y-(WP_{i-2})_y}{(WP_{i-1})_x-(WP_{i-2})_x} \quad (12)$$
Step 3	Find the point which satisfies following condition. $$\{E_i \mid dist(E_i,WP_{i-1})=\frac{R}{2},\quad i=2,3,...\} \quad (13)$$ If there are no points to be satisfied, this procedure is terminated. Otherwise, go to Step 4.
Step 4	Find the one point among the points selected in Step 2 by using these conditions. $$WP_i=\min\{\frac{E_{iy}-(WP_{i-1})_y}{E_{ix}-(WP_{i-1})_x}-(\text{direction angle}),\quad i=2\} \quad (14)$$ $$WP_i=\min\{\frac{E_{iy}-(WP_{i-1})_y}{E_{ix}-(WP_{i-1})_x}-\frac{(WP_{i-1})_y-(WP_{i-2})_y}{(WP_{i-1})_x-(WP_{i-2})_x},\quad i\geq 3\} \quad (15)$$
Step 5	Go to Step 2.

Table 2. Pseudo code for Grid point-based algorithm on the simple field

Step 1	Set the points by Eqs. (1) ~ (3).
Step 2	Rotate the points solved at Step 1 by Eqs. (4) ~ (5)
Step 3	Translate the points solved at Step 2 by Eqs. (6)~(7)
Step 4	Determine whether each solved point is inside the field or not by using Eqs. (8) ~ (11)
Step 5	Select waypoints among the points solved at Step 4. The main procedure is on the Table 1.

Obstacle Avoidance

The main advantage of this algorithm is that this method is well applied even obstacle has a complex shape while the main procedure is simple. To filter the points which are located on the obstacles, the discriminants are used. Those discriminants are similar to Eqs. (8) ~ (11).

$$\theta_i=\tan^{-1}\left(\frac{BP_{y(i+1)}-BP_{yi}}{BP_{x(i+1)}-BP_{xi}}\right) \quad (16)$$

$$\begin{bmatrix} D_{xj}' \\ D_{yj}' \end{bmatrix}=\begin{bmatrix} \cos(-\theta_i) & -\sin(-\theta_i) \\ \sin(-\theta_i) & \cos(-\theta_i) \end{bmatrix}\begin{bmatrix} D_{xj} \\ D_{yj} \end{bmatrix}=\begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix}\begin{bmatrix} D_{xj} \\ D_{yj} \end{bmatrix} \quad (17)$$

Eqs.(16) and (17) shows the calibrated points to decide whether those points are inside of the obstacles or not. An angle θ is an internal angle between two edges of the obstacles. Because to judge the point for the obstacles is the opposite case from the former case which is introduced on the former section, Eqs.(10) and (11) should be changed as Eqs. (18) and (19). If the sequence of vertex is clockwise direction, which means that the boundary edges enclose the obstacle on clockwise direction,

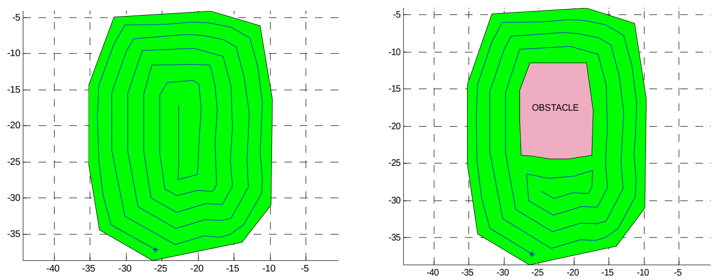

Fig. 4. Result using Grid point−based algorithm (left side) and result for the field with obstacle(right side)

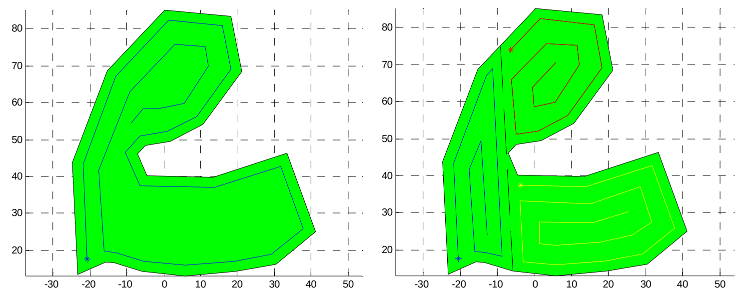

Fig. 5. Comparison with results: without and with decomposition

$$E_x = \{(D_i)_x' \mid (D_i)_x' < -\frac{R}{2}\} \quad . \qquad (18)$$
$$E_y = \{(D_i)_y' \mid (D_i)_y' < -\frac{R}{2}\}$$

Otherwise,

$$E_x = \{(D_i)_x' \mid (D_i)_x' > \frac{R}{2}\} \quad . \qquad (19)$$
$$E_y = \{(D_i)_y' \mid (D_i)_y' > \frac{R}{2}\}$$

The left side of Fig. 4 shows the result path if there is an obstacle on the agricultural field. It shows that this algorithm can detect and avoid the obstacles automatically while the main goal of the work is well performed. However, this fundamental algorithm has a critical defect if the field has some convex edges. To avoid this situation, the field should be simple it does not have any convex edges, and some modifications to a given field is required. In this research, the trapezoidal decomposition process is used before the proposed algorithm is applied. A given field on Fig. 5 has a convex corner which requires some modifications. This figure shows that the necessity to use that decomposition technique, which method, so called “split and merge decomposing” is being well used on the coverage path planning problem to simplify[9].

Modified Boustrophedon Algorithm

Fundamental Description

The other proposed algorithm is based on the back−and−forth motion, so called “*boustrophedon algorithm*”. This approach is widely used in the coverage problem, and it guarantees that there is no overlapped region. Therefore, this approach can be well defined about the rules which are defined on section 2.

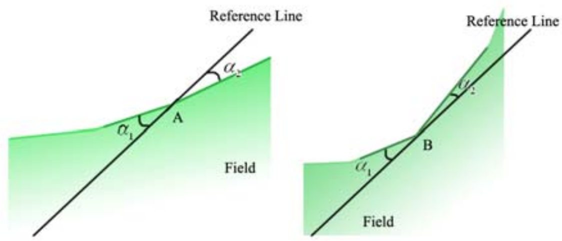

Fig. 6. Dividing point

However, there is a major issue to use this method. When this algorithm is used, the shape should be analytical like the former algorithm, and efficient cell decomposition is required. One of the techniques to divide the complex polygon, exact cell decomposition is powerful and widely used on the path planning [9]. In this research, the dividing point is used. The concept of this point is represented in Fig. 6. Reference line has the same direction as the driving direction. Left side of this figure shows that the normal case among the vertices of the field, and a boundary point A is not a dividing point. However, the special case, which is shown in the right side of Fig. 6, has the dividing point which is a point B. Therefore, the dividing point satisfies the Eq. (20).

$$sign(\alpha_1) = -sign(\alpha_2) \tag{20}$$

Driving direction is another issue to find an efficient path on the coverage path planning problem. In this paper, certain cost function which is related on the length of the driving direction and the orthogonal direction to the driving direction for each component from the decomposition. Eq. (21) shows the cost function to find an adequate driving direction for crop dusting. Fig. 7 shows that how those points are selected and how to use the decomposition. The field in this figure is complex because there are seven convex corners. After defining the reference line and dividing points, three components are generated which are simple to analyze because there is no convex corners with respect to the reference line.

$$\min J = \sum_{i=1}^{n} \begin{bmatrix} \{\text{length with respect to driving direction}\} \\ +\{\text{length with respect to orthogonal direction}\})\} \end{bmatrix} \tag{21}$$

Table 3. Pseudo code for Modified boustrophedon algorithm

Step 1	Find an optimized direction for exact cell decomposition by using the cost function which is Eq. (21)
Step 2	Take the boustrophedon algorithm for each cell.

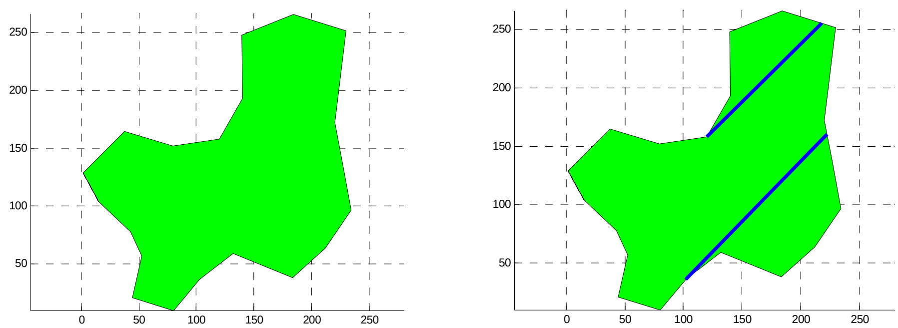

Fig. 7. Given complex field (left side) and decomposed field (right side)

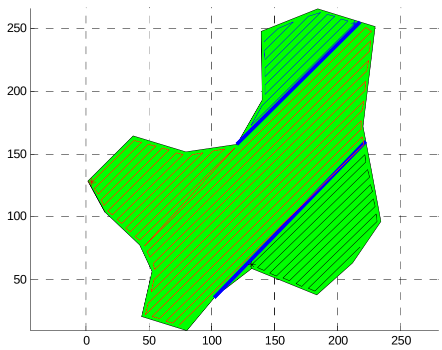

Fig. 8. Result path for the field without obstacles

Table 3 is the pseudo code for this algorithm. The main procedure of this algorithm is similar to the *boustrophedon algorithm,* but there is an innovation to take decomposition. Fig. 8 shows the result after taking the proposed algorithm and this result is admissible.

Obstacle Avoidance

In this algorithm, obstacles on the field are classified by two types. If an obstacle is in the circle which radius is R, this obstacle can be regard as "type A obstacle". Otherwise, it is classified as "type B obstacle". Because type A is too small, it is not considered under decomposition. When back−and−forth mode is proceeded, the helicopter just avoid obstacles belonged to type A, and the pesticide is not sprayed when a helicopter avoid that obstacle. In the case of type B, the edges of that obstacle are considered part of boundary edges of the field.

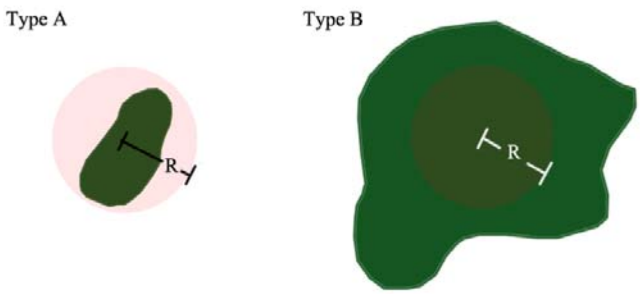

Fig. 9. Classification of obstacles

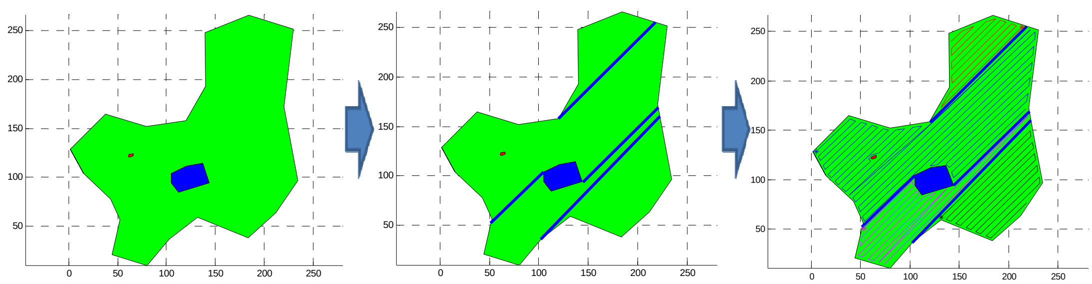

Fig. 10. Main procedure for the field with two obstacle types

Fig.10 shows how to use this method in the case of the field with obstacles. As this figure shows, there are two obstacles on that field. One is small so that can be considered as type A. However, the other one should be considered as type B because the circle which radius is R cannot cover the whole of that obstacle. When the cell decomposition is proceeded, we do not consider the small one as certain boundary points. However, if the back and forth algorithm is used, the path is made that enclose the small obstacles. In Fig. 10, 4 components and 4 sub paths are generated.

Multi-agent Crop Dusting

Multi-agent crop dusting is powerful owing to the low operation time. To get the path for each helicopter, the approach which is related on the operation time about whole path on the field is used. The main idea is to find the paths that satisfy the cost function, which is Eq. (22), which minimize the operated time. In that case, each helicopter should have almost same cost time.

$$\min J = \int_0^{t_f} dt \tag{22}$$

Fig. 11 shows the snapshots by using the multiple unmanned helicopters under the mission. In this mission, an actual agricultural field is considered. 4 helicopters are used on that algorithm, and it is well operated from the result.

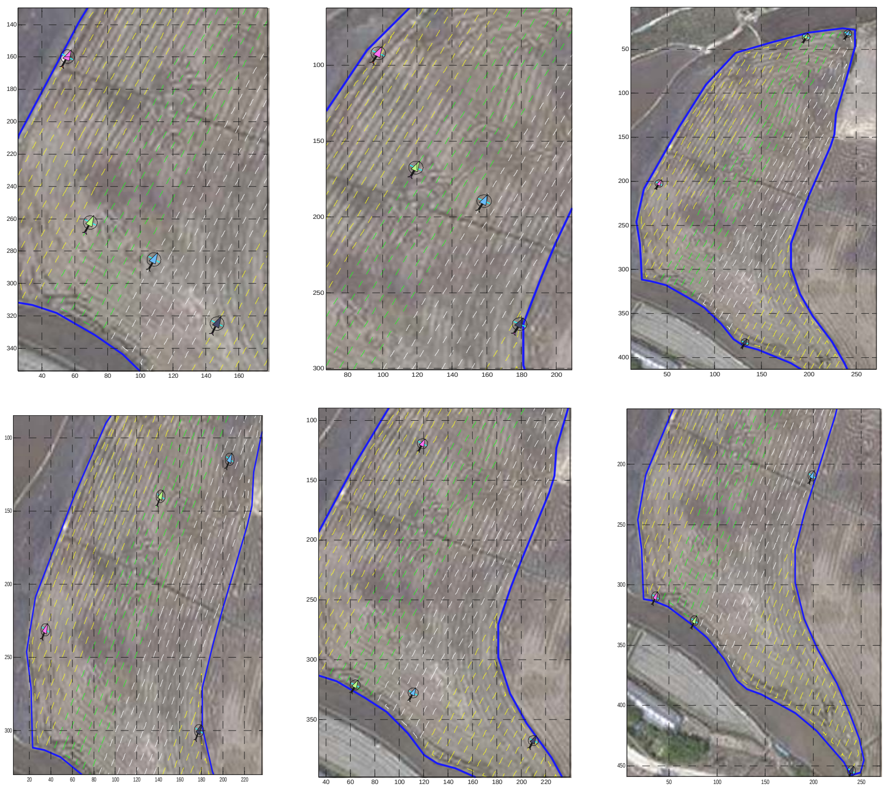

Fig. 11. Multi-agent crop-dusting (4 Helicopters)

Conclusion

In this paper, two algorithms for the path planning for agriculture helicopters are presented. One is Grid point-based algorithm which makes the grid point which can be the waypoints. This proposed algorithm does not have to consider the obstacles seriously, but some cell decompositions are required for the complex fields.

The other algorithm is Modified boustrophedon algorithm. Boustrophedon algorithm is widely used in coverage path planning field, and some modifications are presented in this paper. In this research, exact cell decomposition which decomposes the whole given field to several subfields without overlapped region is used. When this decomposition is used, the dividing points are presented for the efficient path planning. In addition, the obstacles are classified to two types in this algorithm. This approach makes the path planning flexible for complex field, and it is powerful to use for multi-agent crop dusting.

All presented algorithms are based on the waypoint-based path planning. Although those two algorithms doesn't have optimal value for the path to solve, those approaches has an advantage that it can be used any kind of field, especially, for the fields in Korea because the field in Korea has simple shape such as rectangle or trapezoid.

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