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PATH PLANNING FOR PRECISION FARMING BASED ON AUTONOMOUS VEHICLES

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Abstract: This paper describes the path planning system for precision farming based on autonomous tractor with GPS. In order to use the autonomous tractor for the precision farming, we classify the path planning problems into three types. One is the path along the furrows in a crop field. Another type is the path for the replenishment. Third type is the path for working in a meadow or snowy field. Especially, to generate the optimum paths at the planning of meadow, we formulate the covering problem and apply the approach using genetic algorithm. *Copyright © 2001 IFAC*

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1. INTRODUCTION

Precision farming or precision agriculture can be defined as the use of information technologies to obtain knowledge about important crop parameters, and to optimize production system management on an appropriate scale. It is a concept that it has gaining a great deal of attention in recently. In order to realize a site-specific management as precision farming, computer-controlled actuators, for example, fertilizer applicator, sprayer, are required. Furthermore, autonomous tractor that can trace precise positions will be more preferred to increase the effectiveness of the precision farming (Hara 99). Here, we assume an autonomous tractor can receive the GPS signals to take precise positions itself. Namely, precise navigation of an autonomous tractor, without winding like as human operator, will make advantage to utilize the field more effectively.

To use these machines effectively, field information systems (FIS) are required. The FIS must store sensing data of fields and create site-specific working plans from those data. Ordinary, GISs are used as FISs because functions of these FISs are remaining to store the sensing data and create the site-specific working plans. However, to increase the effectiveness of the precision farming, the autonomous tractors will be required and the FIS should be treats the information of the tractors. Thus, FIS should create the plan not only site specific working plans but also make the control plans of autonomous tractor combined with the site specific working plans. We develop the FIS that includes navigation planning. Our developing plans must include attributes for the control plans of actuators. In this paper, we describe the functions, especially the path planning of the system. To generate the optimum paths, we formulate the covering problem and apply the approach using genetic algorithm.

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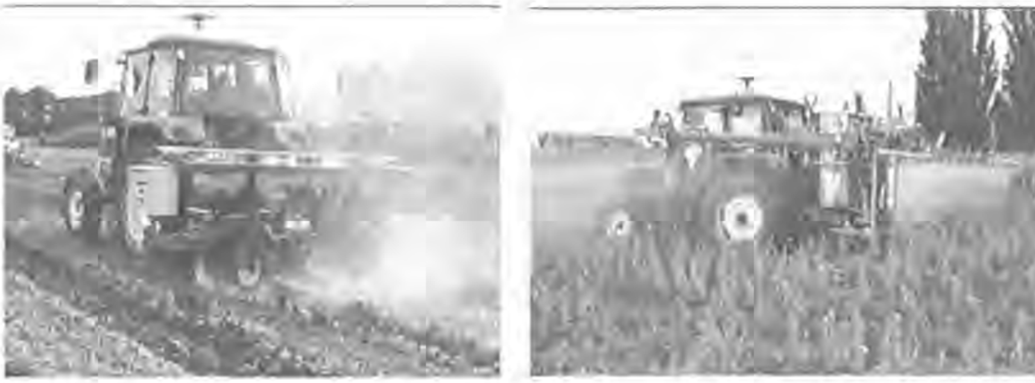

Fig. 1. Autonomous tractor with computer controlled fertilizer (right) and sprayer (left).

Fig. 2. Autonomous crawler which can run in snow field and scatter melting powder of snow.

2. PRECISION FARMING WITH AUTONOMOUS TRACTOR

Today, precision farming is motivated by the economic and environmental concern of excessive applications of chemical and other agricultural inputs regardless of within-field variability. The concept of precision farming is to treat within-field variability. Since soils within a field vary in productivity, optimum use of resources cannot be achieved by conventional farming, uniform applications of seed, fertilizer, pesticides, etc., across an entire field. Implementation becomes feasible only with the development of modern electronic tools. These tools include sensors to measure the many variables affecting crop production, the GPS (global positioning system) for geo-referencing of the data, a GIS (geographic information system) for handling the geo-referenced data, and variable rate applicators able to vary application rates as the applicator traverses a field. Successful implementation of precision farming will reduce both financial costs and environmental damages, and improve in total productivity. The standard cycle of general precision farming is

(1) sensing the data of within-field variability,
(2) producing of field information maps from sensed data,
(3) planning application map based on the field information maps,
(4) operation in field based on application map.

Autonomous tractors based on GPS are been developing in recently for decreasing efforts of the human operators. These tractors can run precisely without human operator by referring the position given from GPS. By applying these tractors, effectiveness of the precision farming will be increased. However, to increase the effectiveness, the tractors are required not only to run in the field without operator, but also to cooperate with variable actuators. Most advanced tractors have a control area network (CAN) to realize these cooperations. As one of such advanced tractors, we develop the autonomous tractors based on KUBOTA MD-77, autonomous crawler vehicle based on ISHIKARI ZOUKI US-D and, as variable actuators, computer controlled sprayer and fertilizer applicator (Hara 99). Supported by CAN and several control systems, the cooperated works can be achieved between the tractor and these actuators (Okuno 00). For example, the precise navigation will enable to precise planting. The precise planting will increase the utilization of field. According to the recording data of planting, the fertilizer applicator and sprayer only work in the planting area. Because the work area can be decided correctly, the required amount of fertilizer and chemicals can be determined. Thus, economical and effective farming will be realized.

3. PATH PLANNING

In this research, the navigation planning can be divided into three according to the kind of farming.

Path planning for working in a crop field The working of the tractors in a crop filed must avoid treading on the crops and keep appropriate velocity. Therefore, the autonomous vehicles working in the filed are required to realize the precise navigation ability. The autonomous tractor, we use, has 2-5 cm accuracy of moving and can keep higher velocity than it operated by human. Based on the abilities of the tractor, planning of the path is mainly to make parallel path to increase the planting area. Because the specification of the path, for example, the pitch between the path is predetermined by the kind of planting crop, the sift and rotation of the path are mainly considered to make the path. The path is fixed after planting. Therefore, the planting position is stored and reused to generate for next works. Thus, the generation of the path position is relatively easy, however, the order of path for works and control of the PF actuator will be different in each work.

Path planning for replenishment in a field The works of spraying and fertilizing are required the replenishment. Therefore, to use the autonomous tractor effectively, it is insufficient only to follow the furrows in the planting area. The autonomous tractor should move to the place for the replenishment autonomously. To realize this ability, the path for replenishment must be generated. The path will consist of the end point of work to the place of the replenishment. The field shape for the path will be narrow. In the limited space, the path length is to be optimized including turn motion and switch back turn if there are required. The required accuracy of the moving is 5-50cm to avoid the obstacles along the filed. Most important property for the replenishment path generation is feasibility. Namely, the paths for the turn motions are constrained by the turn ability of the tractor and the condition of the filed. Therefore, the planning of the path will be constructed by referring the past traces of the turns that were realized by the tractor.

Path planning in meadow and field of snow The purpose of working in meadow is management of grass. In the snow filed, the work is for scattering melting powder of snow. Both work filed consist of polygon shapes, obstacles, and slops. The path for the works is required to maximize the covering of the area with minimal length including curves. The required accuracy of moving is 5-100cm. The accuracy of application is 3-20m. Instead of the low accuracy, the work velocity is relatively higher than that of crop filed. Therefore, not only the optimizations of the path but also the safety without overturning of the vehicle are required. The typical path formations are shuttling work by parallel route or whirling path from edge to center.

In the next sections, we describe the each planning.

4. PATH PLANNING FOR WOKING IN A CROP FIELD

There are two case of path planning for the working in a crop filed. One is the planning of paths starting from the decision of the planting positions. Another case is that the planning obeys the position of the existing furrows. In the later case, the paths for autonomous moving of the tractor are generated from the records of the furrows. The generations of the path positions will be restricted by the position of the furrows; however, the attributes for controlling the tractor and the attached actuators combined with the path positions are generated in each planning.

If the path planning is in the first case, we start from the decision of planting area and theposition of the furrows to realize the effective usage of the crop field. The decision process in the case consist as follows:

(1) Input the parameters of specifications like as the width between furrows.
(2) Decide the direction of furrows in the field to maximize the total path length.
(3) If need, modify the direction of the furrows directly by user.
(4) Secure the side roads as turn area for the tractor.
(5) Make path to follow the furrows include attributes for realizing the precision farming process.
(6) Assign the order of path to moving of the tractor.
(7) Transfer the path data to the autonomous tractor.

In this planting case, we start to create the furrows to maximize the planting area. Therefore, to determine the planting area, the parameters like as the width of furrows. To determine the positions of furrows, the direction of the furrows and parallel sift of them are determined because we assume to make parallel furrows. If the shape of the field is distorted rectangle, we evaluate the direction to maximize the total length that means to maximize the planting area. After the modification of the furrows by the user, the areas of the side roads for turning the tractor are secured. These areas are used for turning of the tractor to connect the paths and moving to the replenishment place.

According to the kind of the works and the function of the applicators, the positions of the paths are calculated. For example, the fertilizer applicator can fertilize 4 furrows at once and the planting actuator can plant at two furrows at once. Based on the ability of the actuator, the paths are set to cover the all furrows. Therefore, the number of the paths is determined from the

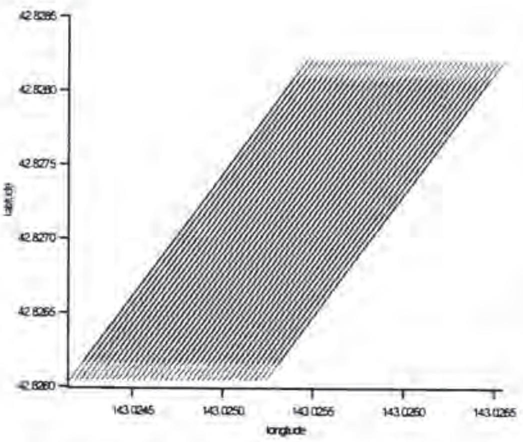

Fig. 3. The result of the paths for fertilizing in the real field of sugar beet.

number of the furrows in the filed divided by the number of the capability of the applicator.

The boundaries between the area of the furrows and the area of side road determine the both ends of paths. The point of the both ends means the start points and the end points of the work along the path. In the working area long the paths, the plan for the position-based control of the applicators is made according to the kind of works. The working process in the paths requires the cooperation between the tractor and the applicator. The cooperation includes the revolution of engine, the status of PTO, the lift arm position, and the status of applicator. Namely, in each path, we have to decide the status of control approaching to start points of the paths, the position based control in each points on the paths, and leaving status at the end points. According to the position based control strategies, the attributes of the points in the paths are decided.

In order to connect the paths, the tractor can turn autonomously without guidance or operation of human. Ordinary, because the distances between the paths are narrow, the turn motion will consists of the maximum angle of the steering and the switch back. The path during the turn of tractor with maximum angle of the steering will easily change affected by the field conditions, therefore it is hard to plan the path of turn precisely. Instead of the turning path deciding precisely, required turning areas are planned. The plan of the areas is to consider the margin from the edge of the field. Namely, it is referred the past records of turns by performing the autonomous vehicles to decide these margins. The tractor assumes to realize the turn action autonomously under the constraints of the assigned turn area. If the tractor can't achieve the turn action in the limited area affected by the wrong condition, like as slipping, the tractor stops immediately to avoid beyond the area.

Based on the above turn ability of the tractor, the order of the paths to connect is considered. Simple case will be to connect the adjacent paths in turn. However, the some kinds of works are required to connect the paths by specific rules. Thus, throughout the selection of the rules for connecting the paths, user can designate the order of the paths. Throughout the above planning process, the path plan can be constructed and transferred to the navigation controller on the tractor.

Fig. 3 shows the example of the plan in a real filed. The filed is designed to have the 152 furrows for the sugar beet in the planning. For the work of the fertilizer in the filed, the 38 paths are made from the path planning process like as the figures.

5. REPLENISHMENT PATH PLANNING

In the case of fertilizing, it is necessary to replenish the fertilizer when the applicator exhausts in the tank. For the driverless operation through the whole work, the path for the replenishment also should be planed automatically. The plan is considered after the control strategies in each path are fixed. Based on the control strategies in each path, the amount of the required fertilizer in each path can be calculated. Because the size of the tank on the applicator is fixed, the planning system can predicate when the tractor should move to the place of replenishment. The restriction concerning the prediction is to avoid the exhausting on the path of working. Therefore, the planning system must specify two points. Namely, there are the end of the path place where it is required the replenishment and restart point of the path for the work after the replenishment. In order to make the path for the replenishment, two types of turn methods, type A and the type B shown in Fig. 5, are prepared to change the direction toward the place of the replenishment. The type A is the case that there is enough area on either side to turn. The type B is the case that there is a area only one side to turn. These turn paths are generated as follow rules.

(1) Turn to the other side of replenishment point. (Type A)
(1) Turn to the side of replenishment point. (Type B)
(2) Find the switch point, and Turn to the field edge just under the start point. (Type B)
(3) Switchback at the edge of the area.
(4) Turn to the side of replenishment point backward.

After the turn path generated, the path are added to reach the replenishment place. The result of the paths for the replenishment in the real filed is shown in the Fig.??.

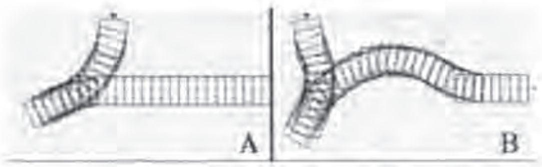

Fig. 4. The two types of the turn paths for changing the toward to moving the place of the replenishment.

6. PATH PLANNING FOR WORKING IN MEADOW

The purpose of the planning is for the works scattering the fertilizer or the melting powder of snow. The scattering works are required covering the whole filed with the fertilizer or the powder. The formation of the paths for the scattering work has a fewer restrictions comparing the work in crop fields. The path planning is required to keep higher velocity and allowed to use the curving paths. Moreover, if the obstacle can be avoided, the accuracy of the navigation is enough less than 50cm. Therefore the paths include the curving parts in the planning. To generate the plan satisfying restriction of the autonomous vehicles related to the minimal curving ability, we use the simulation model as follows:

$$\mathbf{x}_i = (x, y, \theta) \in \mathbf{R}^2 \times [0, 2\pi] \quad (1)$$

$$\phi_i \in [-\phi_{\max}, \phi_{\max}] \quad (2)$$

$$\frac{dx}{dt} = v \cos\theta \quad (3)$$

$$\frac{dy}{dt} = v \sin\theta \quad (4)$$

$$\frac{d\theta}{dt} = \frac{v}{L} \tan\phi. \quad (5)$$

where, $\mathbf{x}_i$: vector of configuration, ϕ_i: control input (steering angle) $\phi_{\max}$: maximam value of steering angle, v: velocity (constant) and L: wheel base. We assume the filed is a flat plane, and the slipping are disregarded. We use follow rules to generate the path plan.

- Turns right and left and alternately. (Shuttling work)
- Turn beginning when there is obstacle in constant distance a_1 forward.
- Turn θ_1(constant) at the beginning of turns.
- Adjust the path to become parallel to the edge of the area which has already been covered.

Fig. 5. The result of the paths moving to the replenishment place in the real filed.

The result of this planning is shown in Fig.6. We carried out the experiments with scattering powder of melting snow according to this navigation map.

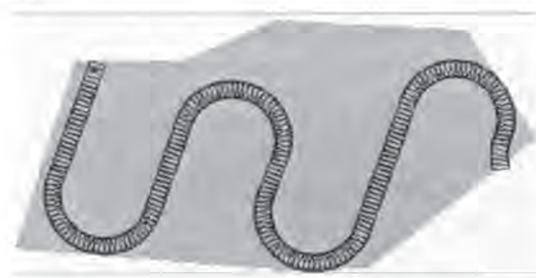

Fig. 6. Paths for working in the meadow applied to the autonomous crawler

7. OPTIMIZATION

It is required that the scattering works covers the whole meadow with a minimal path, which is constrained with a moving ability of the autonomous vehicle. To optimize the paths in the meadow, we formulate this problem as an optimization problem. The works are assumed to scatter with constant width. To express the information about the state of covering, we define the state vector $\mathbf{Q}$;

$$\mathbf{Q}_i = \begin{pmatrix} s_{11} & s_{12} & \cdots & s_{1v} \\ s_{21} & s_{22} & \cdots & s_{2v} \\ \vdots & \vdots & \ddots & \vdots \\ s_{u1} & s_{u2} & \cdots & s_{uv} \end{pmatrix}, \; s \in 1, 0 \quad (6)$$

$$\mathbf{Q}_{i+1} = \mathbf{Q}_i + F(\mathbf{x}_i). \quad (7)$$

The states of the covering are discrete representation dividing by u and v indicate x and y axes respectively. $s_{mn} = 1$ means the cell (m, n) are already worked. $F(\mathbf{x})$ gives the cell $s_{ij} = 1$ the working line crosses and other cell is 0. Initial time is $i = 0$ and end time is $i = t_f$

$$\max . V(\mathbf{Q}_{\mathbf{t_f}}), \; \min . t_f \quad (8)$$

$$V(\mathbf{Q}_{\mathbf{t_f}}) > K \quad (9)$$

$$t_f < t_{\max} \quad (10)$$

$$V = \frac{\sum_{m=1}^{u} \sum_{n=1}^{v} s}{u \times v} \tag{11}$$

where, K : threshold of covered rate, $t_{\max}$: maximum time, $V(\mathbf{Q})$ of equation (8) is an evaluation function, and stand for the rate of the covering. The equation (9) and (10) are restrictions of the rate of the covering and working time.

7.1 *OPTIMIZATION WITH GA*

This covering problem can be regarded as one of the path planning problem which objective is to find a path to allow the robot to move from the starting position to a goal position. To suppress the high computational cost, evolutionary approaches have been proposed. In this paper, we extend the GA approach to this covering problem. Gene C are designed with the sequence of control inputs, $C = (\phi_0, \ldots, \phi_{t_f})$. The phenotype corresponding C is $P = \{(\mathbf{x}_0, \mathbf{Q}_0), \ldots, (\mathbf{x}_{t_f+1}, \mathbf{Q}_{t_f+1})\}$. Using the fitness function $eval(P)$ as follows, we can optimize the evaluation of the path.

$$\begin{aligned} eval(P) &= w_o Obst(P) + w_l Length(P) \\ &+ w_c Cover(P) + w_{ov} Overlap(P) \\ &+ w_{cu} Curve(P) \end{aligned} \tag{12}$$

where, $Obst(P)$: the number of steps the vehicle stay in obstacle area by following path P, $Length(P)$: the length of the path P, $Cover(P)$: the rate of the covering to the object area by following path P, $Overlap(P)$: the number of cells where work was overlapped, $Curve(P)$: the curvature of path P, and w_i: were weights and empirically determined with typical values, namely, $w_o = -1000$, $w_l = -0.5$, $w_c = -2000$, $w_{ov} = -15$, $w_{cu} = -1.5$. The operators of the GA are addition, deletion, and mutation. In addition and deletion, given locus of gene ϕ_i is copied or deleted. The selection is done by the tournament strategy of size 2.

Fig.7 shows the initial path at generation 0. Fig.8 shows the result of path at the generation 100. In this figure, white tiles are uncovered areas and dark gray tiles denoted the multiple covered areas. From this result, almost area can be covered and the effectiveness of the optimization with GA can be shown.

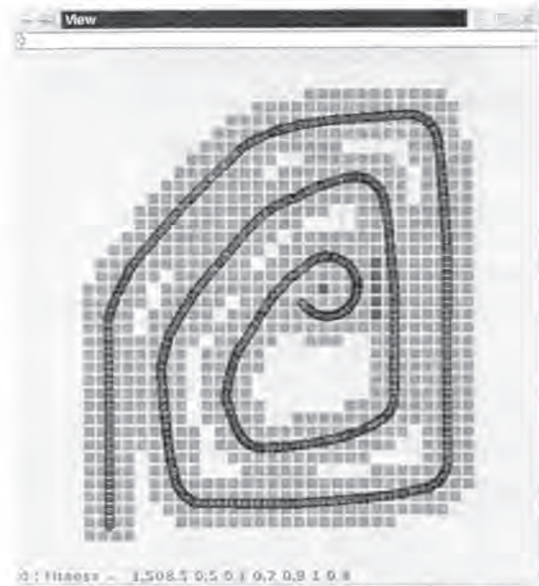

Fig. 7. Path generated by GA at 0 generation.

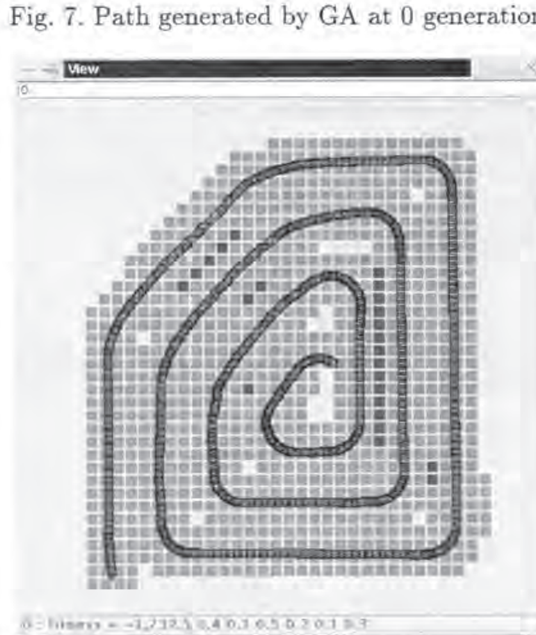

Fig. 8. Path generated by GA at 100 generations

8. CONCLUSION

This paper describes the path planning system for precision farming based on autonomous tractor with GPS. In order to use the autonomous tractor for the precision farming, we classify the path planning problems into three types. Namely, there are the path plannings for working in a crop fieled, replenishment, and meadow. Especially, to generate the optimum paths at the planning of meadow, we formulate the covering problem and apply the approach using genetic algorithm and confirm the effectiveness.

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