Path Planning for Complete Coverage with Agricultural Machines

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Abstract. The problem of planning reference trajectories for agricultural machines is considered. A path planning algorithm to perform various kinds of farm-works is described. The case of convex fields is first considered. A direction of work being given, the algorithm determines the turning areas and selects a trajectory which guarantees the complete field coverage while minimizing overlapping. The method is extended to the case of fields with more complex shape including possibly obstacles. Simulations are proposed to illustrate the reasoning.

1 Introduction

This paper presents a research work issued from a collaboration between RENAULT Agriculture and the LAAS-CNRS which concerns the automatic guidance of high-end farm tractors on the base of GPS data. Steering strategies can be divided into two classes: relative guidance and absolute guidance. Relative guidance consists steering the vehicle by regulating its posture with respect to the track resulting from the previous passage (crop or ploughing line). In that case, trajectories are often rectilinear and parallel. Absolute guidance consists in tracking a reference path, or a trajectory, issued from a path planning strategy [4], [6] Our work deals with the absolute guidance problem. It focuses on the description of a trajectory planning algorithm which provides a field coverage strategy adapted to various kinds of farm-works [15], [10]. The main difficulty of the problem comes from the need to realize the complete covering of the field, that is including the regions inside which the manoeuvre are executed. Planning the trajectories inside the manoeuvre area states a difficult problem which is crucial for agricultural applications. Indeed, while these zones are usually covered at the end when ploughing, they need to be worked at the beginning when harvesting. Previous work devoted to the coverage problem only provide algorithms for the case of simple rectangular areas and do not address the planning problem inside manoeuvre areas. In [16], [1] [5], [13], cellular decomposition approaches have been proposed based on breaking down the workspace. The Spiral-STC algorithm proposed in [9] is based on a discretization of the working area and the definition of a spanning tree to solve coverage. Considering fields with more complex shapes states another difficult problem. Indeed, in that case the working direction may differ from a region to another and a cell decomposition

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has to be done. Such an approach is proposed in [11] where a sequence of sub-regions is selected with different planar sweep lines to compute the coverage path. Theoretical results based on computational geometry can be found in [2], [3].

The algorithm presented in this paper allows to determine automatically the manoeuvre areas and select a covering trajectory which minimizes overlapping. The planning approach is first presented in the case of convex fields. Two strategies are proposed to this end. On this base the presence of obstacle is then considered and the method is extended to the case of fields with more convex shape.

2 The Automatic Guidance Project

The path planning algorithm presented in this paper comes as a part of an industrial project of RENAULT Agriculture which aims at developing autonomous navigation abilities for farm tractors.

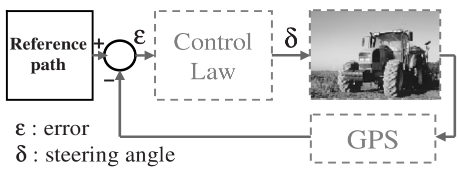

Fig. 1. Farm tractor control system overview

The GPS-based farm tractor control system is based upon the following four units (figure 1):

- The sensor: Real-time, kinematic GPS . Its high three dimensional (3D) accuracy ($\sigma < 2cm$) and its low latency ($t_{latency} < 0.2s$, see [7]) allow its use in a closed loop system. It outputs information about position and velocity of one point of the vehicle to control.
- The farm tractor to control: The only technical requirement is the availability of a model with an electro-hydraulic power steering instead of an all-hydraulic one. The steering angle can by supplied either by the driver, thanks to the driving wheel, or by the embedded computer.
- The Controller implemented on an embedded computer: The system is able to follow paths at various velocities [14,6] with an accuracy better than 10cm.
- The trajectory planner which determines the reference path to follow to perform a specific farm-work.

This paper focuses on the fourth unit only, namely the path planning problem.

3 Covering Path Planning

Farm-work experiments have proven that the choice of the working direction within the field has to be guided by two major factors. First, to reduce sliding and traction efforts, the tractor must move at best in the direction of the slope and execute trajectories with very low curvature. Second, to reduce the number of manoeuvres, the direction of motion must be, as far as possible, parallel to the longer side of the field. In particular, in wedge-shaped regions, the motion must be parallel to one of the edges. To satisfy these constraints at best, it appears necessary to decompose the field into regions, and define in each of them a "Steering edge" *S-edge* which will guide the successive tracks. Furthermore, when planning trajectories, it is necessary to determine regions called "Turning areas" *T-areas*, located at extremities of the field, inside which the tractor will execute U-turns or manoeuvres. The width of T-areas depends on the tractor's characteristics and the nature of the tool.

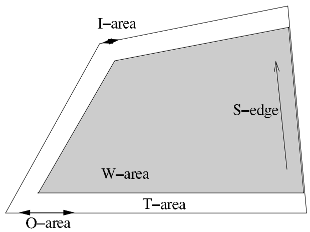

Fig. 2. Definitions

The remaining part of the field constitutes the "working-area", *W-area*. Inside this central region, the farm-work trajectories are most part of time rectilinear parallel tracks directed along the *S-edge*.

The algorithm proposed in this paper applies to polygonal fields including at most one vertex of concavity. An extension is proposed to consider the case of fields including one moderate curved boundary, that is one smooth low-curved boundary along which the tractor can move. This restriction allows to consider most part of fields encountered in real applications. For such a field, once the input area, *I-area*, and the output area, *O-area*, have been defined on the field's boundary, the path-planning problem can be stated as follows:

Determine a trajectory starting from a point in the I-area and ending at a point of the O-area which guarantees the coverage of the whole field (W-area + T-areas) while minimizing the overlapping between adjacent tracks and the number of manoeuvres.

Note that, depending on the nature of farm-work, the covering of the T-areas is done at the beginning or at the end of the task. For instance, when ploughing the *T-areas* are to be covered at the end, while they are worked at the beginning during harvest. The algorithm is based on the partitioning of the field into convex polygons. The partitioning process is described in section 3.3. Inside each convex polygon, a *S-edge* is determined and a set of characteristic points is defined at the boundary of the W-areas and the T-areas. These points will constitute the nodes of a graph upon which the trajectory is defined. Two strategies are proposed to this end. The trajectory planning strategy is first described for the case of a convex polygon free of obstacles in section 3.1. The presence of obstacles is considered in section 3.2. Depending on the size of the obstacles two avoidance strategies are proposed. Finally, section 3.4 describes the extension of the method to the case of fields including one moderate curved border.

3.1 Case of Convex Polygonal Fields

This section presents the trajectory planning method for the case of a convex polygon free of obstacles. The input data are the *S-edge*, the *I-area*, the *O-area*, the kind of farm-work to be executed and the characteristics of the tractor and the tool (type, width, curvature radius).

The path planning strategy is based on three successive steps. The first one is a topological representation of the field which consists of determining a set of characteristic points from which a graph is defined (section 3.1). On this base, two strategies are proposed to construct the reference trajectory.

Determination of characteristic points Once the S-edge is specified, the T-areas are computed by taking into account the space required to perform the turning manoeuvres. In practice, this space is a whole number of the tracks width. This implies to shift or add a pair of characteristic points to guarantee the field coverage without overflow. Outside the T-areas, the field is covered by parallel tracks directed along the S-edge. The tracks are arranged in such a way to insure the complete field covering while minimizing overlapping. Following the same technique, the T-areas are also covered by parallel tracks but directed along the side-edges. The end points of all working-tracks are considered as characteristic points (see figure 3 left).

Construction of the trajectory In order to construct of the trajectory, the characteristic points are considered as the nodes of a graph. Two strategies are proposed to define the arcs and explore this graph. The first one is based on the search for the best Hamiltonian path according to the minimization of a cost criterion, while the second involves a simpler geometric reasoning.

Hamiltonian graph exploration: Let $X = \{x_1, x_2, \ldots, x_n\}$ be the set of characteristic points defined by the end points of tracks. These points are considered as the nodes of a graph. A set of graph edges $U = \{u_1, u_2, \ldots, u_m\}$ is then defined, representing rectilinear paths between these nodes from which the different kind of farm-work can be synthesized. To achieve a given farm-work, a specific value is assigned to the graph edges. The coverage strategy is deduced from a search within this graph $G(X, U)$. Seven types of edges are to be considered depending on the kind of displacement they represent. A specific value p_i is associated to each type (see figure 3 right):
p_1 : to execute a working track inside the field,
p_2 : to pass from a working track to the next one,
p_3 : to jump from a working track to a track located one after the next one (to avoid manoeuvres),
p_4 : to jump from a working track to any other track except the next two,
p_5 : to jump from a working track to a point located inside the T-area,

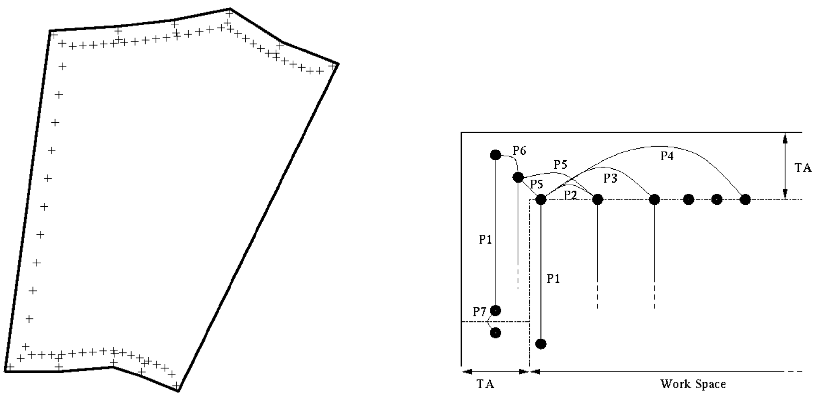

Fig. 3. Characteristic points (left) and arc notation (right)

p_6 : to pass from a working track to the next one inside the T-area,
p_7 : to pass from a T-area to another one.

From the above construction, the determination of a trajectory is based on the search for an Hamiltonian path in the graph $G(X, U)$. If such a path exists, it insures the whole coverage of the field and minimizes the overlapping, as it passes once through each characteristic point. The problem of finding an Hamiltonian cycle within an undirected graph is NP-complete, i.e. the solution cannot always be found in $O(n^k)$ for k constant. The proposed algorithm is based on the following reasoning. From each node, the edge with maximal weight p_i is selected to reach the next node. This comes to solve a local maximization problem at each step. To evaluate the quality of the solution, a cost criterion depending on path length, working duration, number of U-turns and jumps in T-areas is evaluated. To reduce the computation time an heuristic is introduced which consists of minimizing the set of possible initial points. In practice, the application of this heuristic leads to the optimal solution or to a near optimal solution. Figure 4 shows the final trajectory in the case of a non-convex field. Note that the decomposition in three regions has been done manually.

Geometrical method: Though the previous method allows to determine a near optimal solution when exists, the algorithm complexity is high (NP complete) and therefore highly time-consuming. This fact has motivated the development of a simpler algorithm based on a geometric reasoning. The solutions provided by this second approach turn out to be close to usual agricultural habits.

The reasoning is based on the same set of characteristic points. The idea is to restrict the search for a covering solution to trajectory starting from the external tracks of the *W-area*. As there exist two possible directions of motion along these external tracks, only four solutions are to be considered for each convex polygonal cell. The same reasoning is used to cover the *T-areas*. Note that, depending on the nature of the farm-work, the covering of the *T-areas* has to be done at the beginning or at the end. For each *I-area* and *O-area*, a complete solution is computed to guarantee

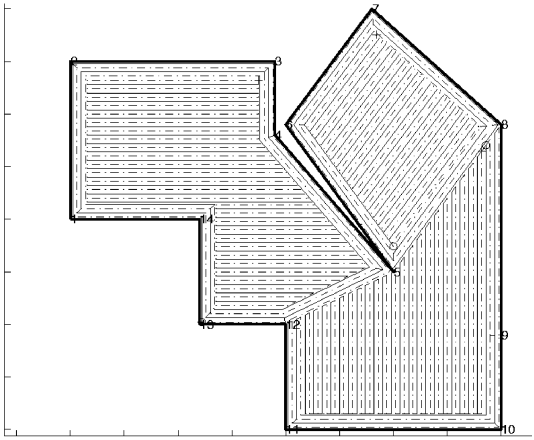

Fig. 4. Solution based on Hamiltonian graph exploration

the whole coverage (*W-areas* + *T-areas*). The algorithm selects the solution along which the cost criterion (which is function of the path length and the number of manoeuvres) is minimized. Figure 5 shows the same field for two *S-edge* directions, note that the number of *T-areas* is different.

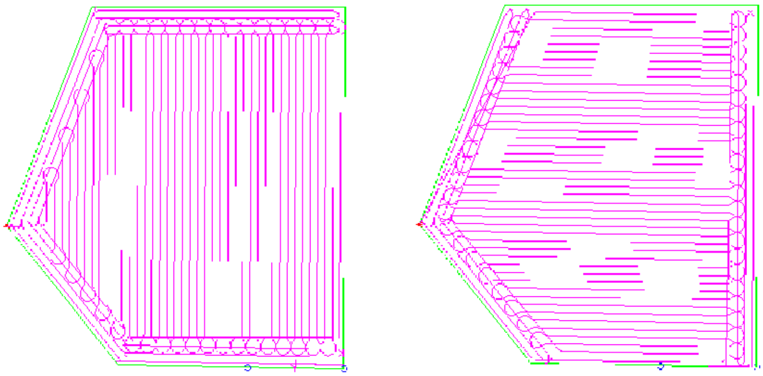

Fig. 5. Example of *T-area*: a unique one (left), or two separate (right)

3.2 Case of Convex Polygonal Fields with Obstacle

The algorithm is restricted to convex polygonal obstacles. Depending on the size of obstacles with respect to the tool width, two navigation strategies are proposed. An obstacle is considered as *small* if it intersects at most three adjacent tracks of the nominal trajectory, otherwise it is referred to as *large*.

Large size obstacles: The case of large size obstacles needs to be considered first as it induces a strong modification of the structure of the nominal trajectory. The method involves a sub-partition of the field into convex cells (see figure 6) and the introduction of an additional *T-area* around each obstacle. These new turning zones will be used to insure the whole coverage and allow the transition between the adjacent cells surrounding the obstacle.

Algorithm 1

```
Sort the obstacle with the top point
Do vertical plane-sweep from top to bottom
if Cell begin with top point obstacle then
    Do Follow-Obstacle (see algorithm 2)
else
    Sweep cell
end if
```

The navigation strategy is defined as follows: sweep the vertical plane, when a new obstacle is detected (algorithm 1) work all the cells around. Start from the cells located on the right side, then climb up to the top of the obstacle and finish by the left cells. At the end of this stage it is necessary to work the *T-area* located around the obstacle. This method guarantees that the tractor will not pass through a cell already worked in order to start working a new one (algorithm 2).

Algorithm 2 Follow-Obstacle

```
Sweep the right cells from top to bottom
if Not new obstacle then
    Sweep cell
else
    Top point obstacle implies Follow-Obstacle
end if
Climb up to the top point
Sweep the left cells from top to bottom
if Not new obstacle then
    Sweep cell
else
    Top point obstacle implies Follow-Obstacle
end if
Work T-area around the obstacle
Change cell
```

Small size obstacles: In this case, the avoidance strategy consists of modifying locally the nominal trajectory. First a covering trajectory is computed for the whole field, by considering the large obstacles, while ignoring the small ones. Each time a track intersects a small obstacle, a local “avoidance-trajectory” starting from the

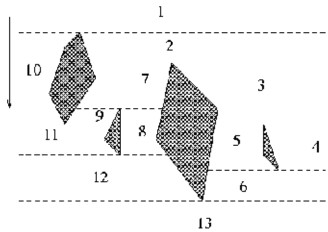

Fig. 6. Sequence of work in the cells

track before the obstacle and reaching back the track beyond it, is computed. The avoidance process is then defined by the following five steps (see figure 7):

- move towards the obstacle along the nominal track until the tractor is close to contact,
- move backwards along the track until the starting point of the avoidance curve is reached[1],
- move along the avoidance curve until the track is reached anew,
- move backwards along the track until the tool is closed to contact,
- move forwards until a new small-size obstacle is detected.

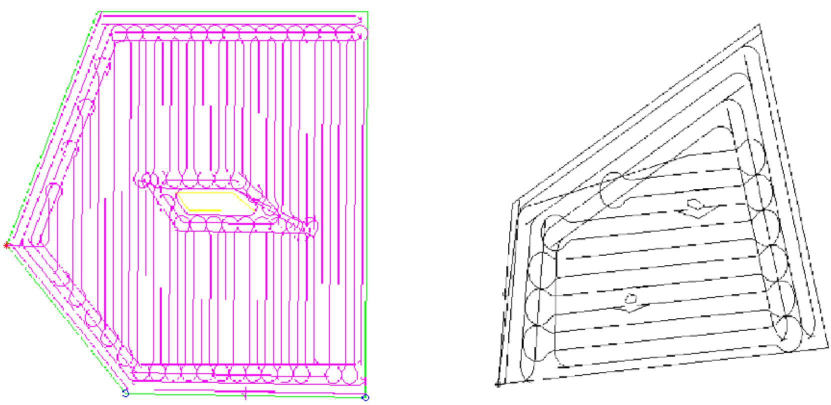

Fig. 7. Examples of obstacle avoidance: large (left) and small (right)

3.3 Case of Nonconvex Polygonal Fields

Let us consider now the upper level of the algorithm, that is the case of polygons including at most one concave vertex (i.e. only one internal angle strictly greater than

[1] In practice a security distance to the obstacle is defined

π). In that case, the method consists in partitioning the field into two adjacent convex cells by defining a boundary segment issued from the concave vertex. The location of the remaining extremity of the boundary segment is chosen so as to minimize its length. Indeed, the partition induces an additional *T-area* which needs to be covered by the trajectory. Finally, in each convex cell the *S-edge* is chosen so as to minimize the number of manoeuvres, or equivalently the number of parallel tracks. The cost criterion associated to the partition is equal to the sum of the costs of the two convex fields plus the length of the additional border segment. This algorithm could be easily extended to consider more complex polygons. Indeed, the partitioning method can be iteratively applied to consider additional vertices of concavity.

3.4 Case of Fields Including One Moderate Curved Boundary

The algorithm has been extended to consider the case of fields including one moderate curved boundary, that is one smooth low-curved boundary along which the tractor can possibly move. The coverage method is based on a convex polygonal approximation of the field and the translation of the curved boundary as follows:

- considering the external vertex construct a convex polygonal hull of the field,
- inside this convex hull, construct a sub-polygon by translating normally the edge corresponding to the curved boundary until it is wholly include in the field,
- by translating the moderate curved boundary, draw the minimal number of curved tracks which are necessary to cover the region of the field located ouside the sub-polygon,

On this base, the trajectory is determined by using the algorithm described in section 3.1 to cover the convex cell, while the remaining part is covered by the successive translated curves (see figure 8). Though the successive translated tracks necessarily overlap, this method guarantees to avoid the singularities that may occur when constructing tangent tracks. Indeed, drawing successive adjacent curved tracks may lead to a rapid increase of their curvature making them no more admissible.

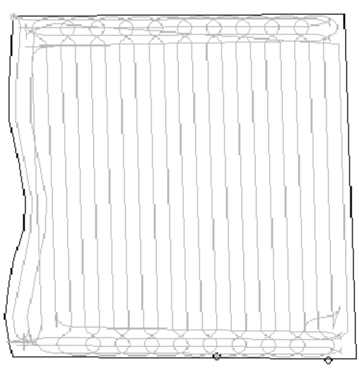

Fig. 8. Example of moderate curved boundary

4 Conclusion

The proposed algorithm based on the treatment of convex cells and the definition of characteristic points can simply be extended to the case of fields with more complex shape. The extension has been studied for the case of fields including one vertex of concavity or one moderate curved boundary. More complex situations could be considered following the same approach. Simulations provide very satisfactory results in the sense that they are realistic and close to the current practices of farmers.

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