Combined coverage path planning for field operations

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Abstract

Searching an optimal path to cover the whole field while fulfil certain agricultural field operation has been found to be extremely difficult problem to solve mathematically or algorithmically. Although area coverage problem has been studied extensively in the robotics literature, most of the developed approaches cannot be used for the case of agricultural field operations due to the special characteristics inherent in these operations.

During the last year, two complementary researches regarding the field coverage planning for agricultural machines have been independently presented. The first approach, using prediction and exhaustive search methods, results the optimum decomposition of a complex-geometry field into sub-fields and the optimum driving direction in each field. The second one, using a heuristic combinatorial optimization algorithm, results the optimal sequence that the machine visits the sub-fields and the optimal traversal sequences of parallel field tracks for each sub-field.

In this paper, a first attempt to connect these two approaches is presented, in order to provide a complete method for field area coverage planning that is directly applicable to autonomous agricultural machines as well as to a next generation of navigation-aid and auto-steering systems. As an implementation of the total method, an example of optimal planning for a given field is given.

Keywords: field coverage planning, autonomous machines, navigation-aid systems agricultural fields, agricultural machines, field traffic

1 Introduction

Searching an optimal path to cover the whole field to fulfil certain agricultural filed operation has been found to be extremely difficult problem to solve mathematically or algorithmically. However, a need for such algorithm or method has been seen during last years as the parallel tracking devices has become more common in tractors and other agricultural machines.

As it is defined in robotics applications, area coverage planning determines a path that guarantees that a unit (or a specific part of it) will pass over every point of the area without overlaps or missed areas while all obstacles must be avoided. This includes the next three procedures (Huang, 2001): 1) decomposition of the coverage region into sub-regions, 2) selection of a sequence of those sub-regions and finally 3) generation of a path that covers each sub-region.

Area coverage planning was motivated by applications such as lawn mowing (Huang et al., 1986), cleaning (Hofner and Schmidt, 1995), mapping unknown environments (Zelinsky et al., 1994), mine detection (Land and Choset, 1998), etc. The proposed algorithms include off-line algorithms (Choset and Pignon, 1997) as well as on-line ones (Hert et al., 1996). Furthermore, the case of multi robot units has been studied (Butler et al., 2000). In Choset (2001) an extensive presentation of relative algorithms is given. Although the problem has been studied extensively in the robotics literature, most of the developed approaches cannot be used without modification for agricultural operations because of the special characteristics inherent in these operations.

During the last year, two researches regarding the field coverage planning for agricultural machines have been independently presented, which by coincidence are complementary to each other. The first approach results the optimum decomposition of a complex-geometry field into sub-fields (blocks) and the optimum driving direction in each field (Oksanen, 2007). The second one presents an algorithmic approach towards computing traversal sequences for parallel field tracks, which improve the machine’s field efficiency by minimizing the total non-working distance travelled (Bochtis, 2008).

In this paper, a first attempt to connect these two approaches is presented, in order to provide a complete method for field area coverage planning directly applicable to autonomous or semi-autonomous (navigation-aided) agricultural machines. In a first stage, using prediction and exhaustive search methods, each field is divided into blocks and for each one of them the driving direction is determined. In a second stage, the optimal sequence that the machine visits the sub-fields is determined and the optimal field-work pattern is produced for each sub-field. For this stage, a combinatorial optimization algorithm was used. This algorithm is based on heuristics operations and has been developed for the special case of agricultural operations. As an implementation of the total method, an example of optimal planning for a given field is given.

2 Method

2.1 First stage: Split into simple subfields

In the first stage a complex field is split into blocks that are easy to operate with straight driving lines or *swaths*. In this algorithm a greedy selection is used, first the best block is found, that is removed from the region and the same algorithm is repeated until the whole field is split.

In the search of the best block at each step, the best driving direction is searched. In several possible driving directions so called *trapezoidal decomposition* is applied in order to split the region to smallest possible pieces, trapezoids. After trapezoidal decomposition, trapezoids which can be merged are merged into *blocks*. The condition for merging includes equal parallel lines and certain requirements for headland angles. After trapezoidal decomposition and merging, the block with best efficiency is selected as the block, which is removed from the region. Algorithm can handle also obstacles in field.

This algorithm also automatically lays headlands. Headlands are only laid at the end of block if the swaths end to edge of field. In other case headland is not needed. It is also possible to take account hills, under drainage and other practical aspects through *regions with prohibited driving directions*. These regions are defined inside field boundaries and for each region unwanted range of driving directions is set. This is counted in selection phase as an obstacle if the driving direction is in the range. Details of the algorithm can be found in (Oksanen, 2007).

Two examples are presented in Figure 1. On left a simple field is presented, this contains 7 blocks and on right is more complex field with obstacle resulting 30 blocks. In both cases the result makes sense.

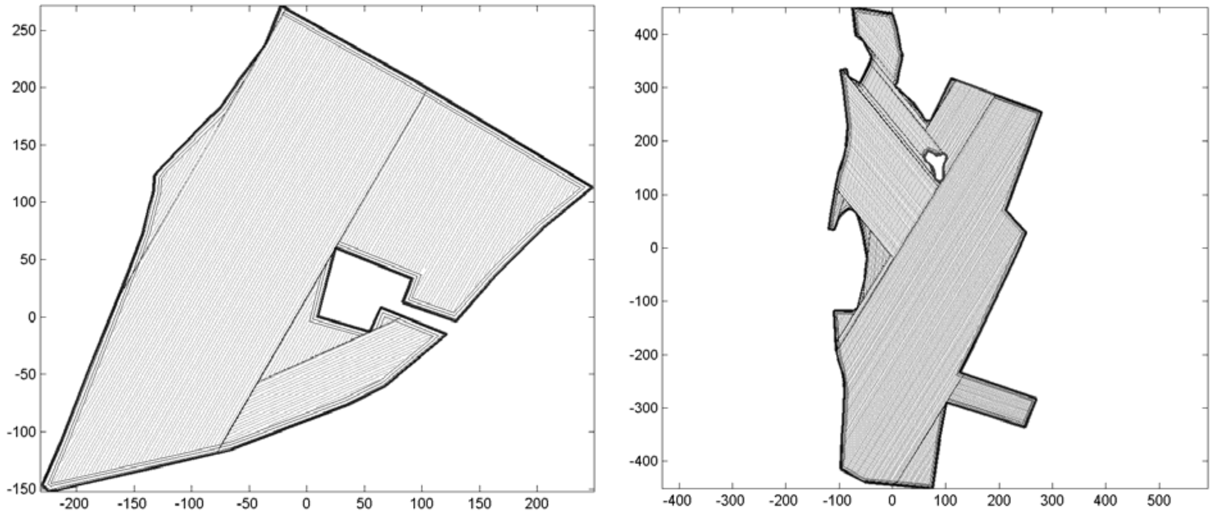

Figure 1 Result from split into subfields algorithm

2.2 *Second Stage: Optimal track sequence generation*

The second stage of the combined method is based on an algorithmic approach towards computing traversal sequences for parallel field swaths (tracks), for one or for numerous fields, covered by one machine or by a fleet of them (Bochtis, 2008). This algorithmic approach improves the field efficiency of the machines, by minimizing the total (in-field and out-field) non working traveled distance. Field coverage is expressed as the traversal of a weighted graph and the problem of finding optimal traversal sequences is equivalent to finding shortest tours in the graph. By doing so, the problem is associated with a complete undirected graph $G = \{S, E\}$ consisting of a set of nodes S, a set of arcs E, and a traversal cost for each arc $a_e, e \equiv \{i, j\} \in E$. In this graph, a solution is the union of k cycles whose only intersection is the node coresponding to the initial location of the machine.

Each field track or swath is represented by two nodes, one for each swath line ending. According to this representation, if set $T = \{1, 2, 3, \ldots\}$ denotes the arbitrarily ordered set of field swath indices (e.g., from left to right), the set of nodes S is written as $S = \{1, 2, 3, ..., 2 \cdot |T|\}$. The nonnegative finite cost associated with each arc depends on the pair of nodes that is connected. It could be defined to be equal to ∞, to zero or to the non-working distance that the agricultural machine has to travel (e.g., the maneuver's length) while executing a headland turn. For the calculations of the length of these headland turns, the agricultural machine is considered as a vehicle able to move forward or backwards in an empty plane (assuming that there are no obstacles in the headlands). The shortest turns are resulted from the implementation of the Dubins’ Theorem and the Reeds-Shepp Theorem for non-holonomic systems (Triggs, 1993).

The traversal of the graph is subject to the constraint that the tour has to be of minimum total cost while each node has to be visited exactly once and any sub-tours should be excluded of a feasible solution. For the solution of the optimization problem a heuristic graph search algorithm was constructed. The algorithm operates in two stages:

i) the randomization phase, where by choosing the best amongst traditional headland fieldwork patterns, e.g. alternation patterns, continuous patterns (Hunt, 2001), an initial solution is building, and

ii) the improvement phase, where various improvement heuristics are performed based on the use of local search techniques e.g. Or-opt operation, 2-opt operations and swap operations (Papadimitriou and Steiglitz, 1998).

Details of the method can be found in (Bochtis, 2007). An implementation of the algorithm on conventional machines can be found in (Bochtis and Vougioukas, 2008) while its implementation to the mission planning on an autonomous tractor can be found in (Bochtis et al., 2009). Figure 2 illustrates a solution from the algorithm implementation – *Hako tractor* developed in University of Copenhagen (Griepentrog and Blackmore, 2007) was used to execute the solution.

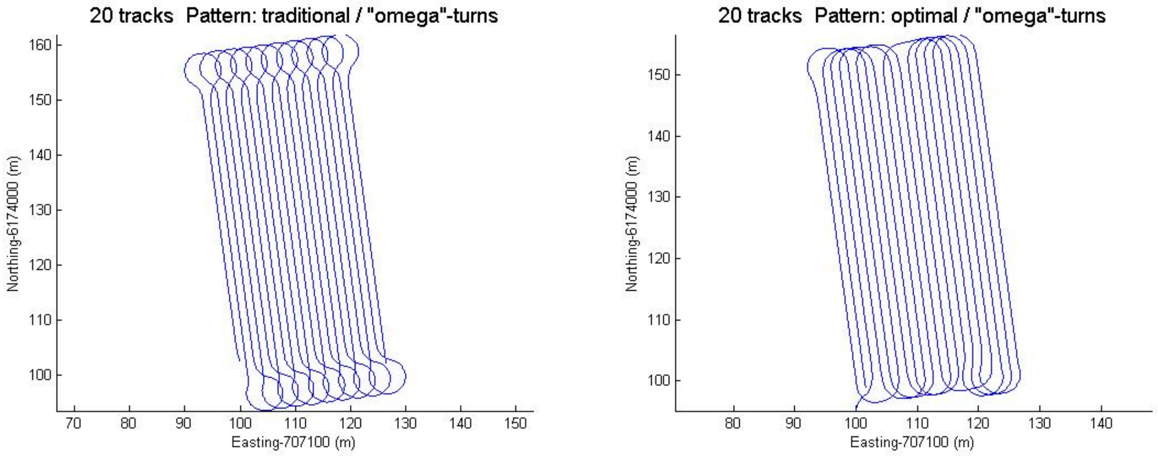

Figure 2 Agricultural coverage operations in a rectangular field based on optimal and on traditional planning.

3 Case Study

The sequentially integration of the two algorithms, is presented through a case study. For a case a real field from Southern Finland was selected (Figure 3 3). Area of the field is 1.00 ha, the working width of machine (for example hitch mounted seed drill) is 2.5m, minimum turning radius is 6m, operational driving speed in swaths is 10 km/h, turning speed is 3km/h, number of headland swaths is 3, so headland width is 3 times the working width.

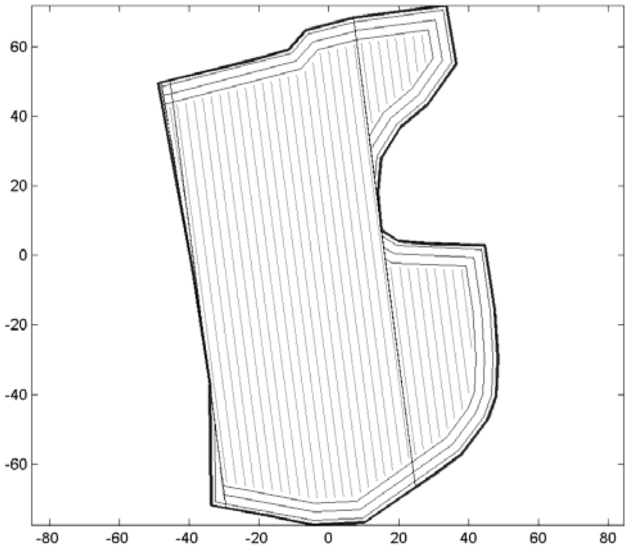

Figure 3 A case field and the split algorithm result.

Split algorithm results 5 blocks, these are shown in Figure 3. Area of the largest block is 0.73 ha, the second largest is 0.17 ha and the third largest 0.084 ha. Rest of the blocks are under 0.001 ha. The result makes sense as the largest block covers most of the field and it results long straight driving lines which provide good efficiency for operation. The main body of the particular field consists of the three largest blocks with number of swaths $|T_1| = 22$, $|T_2| = 8$ and $|T_3| = 9$, respectively. Consequently, the corresponded to the main body graph is composed by three sub-sets e.g. $S = \bigcup_{i\in\{1,2,3\}} S_i$, where the number of the nodes included in each subset is given by: $|S_i| = 2|T_i|, i \in \{1,2,3\}$ (Figure 4).

Concerning the operation at the headland area, it was not included in the optimisation procedure due to the facts, first, the headland area consists of three swaths and there is no meaning for optimizing the corresponding sequence, and second, the order in which the machine operates at the headlands is determined by the type of the operation (for example, in harvesting operations headland area is harvested first while in the seeding operations headland area is seeded last).

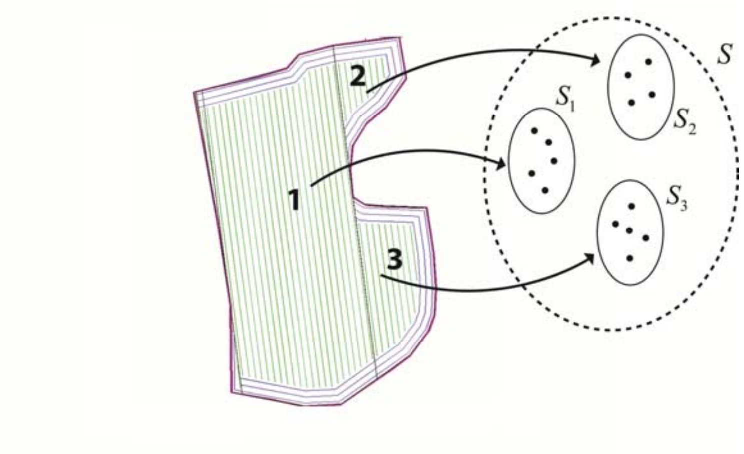

Figure 4 Problem’s topology

As it is easily understudied from the blocks layout, some connections between swaths can be permitted or not, depending on the machine's current moving direction. Let us consider for example, Block 1 and Block 2. If two nodes correspond to the upper endings of two swaths, the connection between them is permitted. In contrast, if two nodes correspond to the lower endings of two swaths, the connection is permitted only if the swaths are elements of the same subset. These restrictions are automatically taken into account by the algorithm, by assigning an infinite cost to the undesirable connections. The topology of the permitted connections for the particular field is depicted in Figure 5Figure.

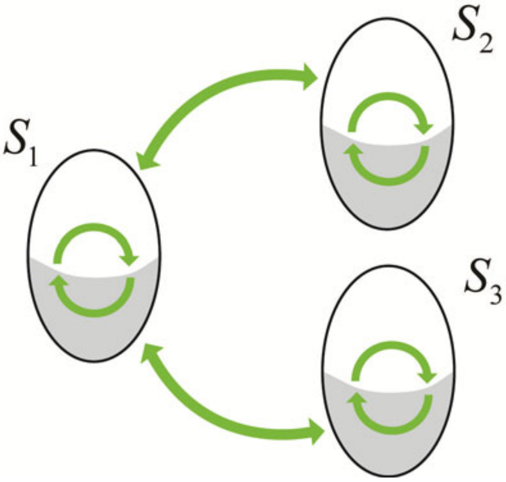

Figure 5 Permitted transitions between sub-sets

From the implementation of the optimization algorithm the optimal swath sequence for the given field is:

$$\sigma^* =< \overbrace{3\ 8\ 2\ 7\ 1\ 6\ 13\ 18\ 12\ 17\ 11\ 16\ 5\ 10\ 15\ 20}^{\text{BLOCK1}}\ \overbrace{27\ 23}^{\text{BLOCK 2}}\ \overbrace{19}^{\text{BLOCK 1}}\ \ldots$$

$$\overbrace{34\ 39\ 33\ 38\ 32\ 37\ 31\ 36\ 35}^{\text{BLOCK 3}}\ \overbrace{21}^{\text{BLOCK 1}}\ \overbrace{26\ 30\ 25\ 29\ 24\ 28}^{\text{BLOCK 2}}\ \overbrace{22\ 14\ 9\ 4}^{\text{BLOCK 1}} >$$

The resulted non-working distance is 1,699.3 m, while the effective distance is 3,125.9 m.

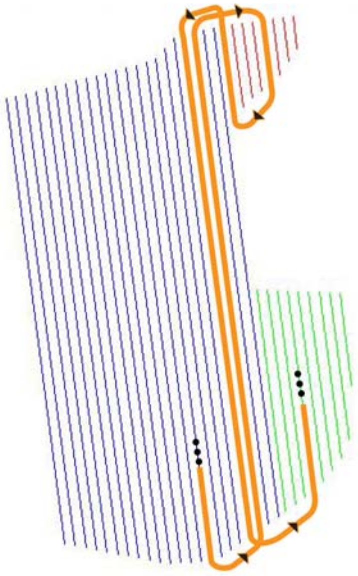

Figure 6 Part of the resulted optimal planning

From the swath sequence, it is obvious that the resulted optimal field-work pattern is not akin to any traditional pattern. Furthermore, this optimal planning is diversified from any traditional planning in the way the machine visits the field blocks. According to the “traditional sense” on the field operation execution, the driver starts working in a block and moves to the next one only after the completion of the work in the first one. In the presented planning, as it is depicted in Figure 6, after operating in swath 20 which belongs to Block 1, the machine is moving to Block 2 where it operates in two swaths (27 and 23). Following, it returns to Block 1 where whilst operating on swath 19 it is moving to Block 3.

4 Conclusions

In this paper, a combined method for field area coverage planning was presented. At the first stage of the method the field at hand is divided into sub-fields/blocks and for each one of them the driving direction is determined. In a second stage, the optimal sequence that the machine visits the blocks is determined and the optimal field-work pattern is produced for each block. The optimality of each one of the two individual parts compose the method, has already presented in past publications. Nonetheless, a quantitative valuation of the combined algorithmic procedure is an issue for further research.

The presented method can easily incorporate the cases of multiple-machines, capacitated operations (where more than one route are required for the completion of the operation) and fields with obstacle regions. Furthermore, based on the research carried out so far, it seems that such an approach can constitute the algorithmic base for a next generation of navigation-aid and auto-steering systems, where the swath and block sequences will determined algorithmically.

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