SPLIT AND MERGE BASED PATH PLANNING FOR AGRICULTURAL MACHINES

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ABSTRACT

If the field plot shape is not rectangular and if it contains obstacles, the coverage path planning problem is hard to solve for a non-omnidirectional machine. Scientists have developed several algorithms to solve this coverage path planning problem, but all of them have pros and cons. If the machines were omnidirectional and turning times were decreased to insignificant, the problem would be quite easy to solve using known robotic path planning methods. Traditional agricultural machines, like tractors, tractor-trailer combinations, self-propelled harvesters and other man-driven machines are slow to turn at headlands. This is the most differentiating property of the problem formulation compared to traditional robotic coverage path planning, which has dealt mainly with omnidirectional kinematics.

In this paper a higher level algorithm to split a complex shaped field plot to smaller parts is presented. The higher level splitting algorithm is presented in detail in this paper. The algorithm can handle any field, including obstacles. The algorithm is based on trapezoidal split, merge and search. The algorithm is suited to any kind of vehicle, which is described with a few parameters, like working width and turning time function. In the latest version, the required headlands are generated automatically and there is also a possibility to define regional restrictions as forbidden driving directions. With this formulation it is possible to take into consideration the previous operations, underdrains and steep gradients.

KEYWORDS. Path planning, mission planning, coverage, field plots, agricultural machines, field robots, agricultural robotics, tractors, guidance, motion control.

INTRODUCTION

Tractors and self propelled farming machines moving on the fields are traditionally driven by a human driver. The human driver has designed the driving strategy of a single field by himself, without any assistance. He/she has chosen the strategy on the basis of type of task, working machine and especially on experience. In family size farms the strategy is based mostly on experience and the driving strategy remains the same over the years. If the field shape is not rectangular or if there are obstacles, the generation of the strategy is not so simple. Usually the most optimal solution is not even the goal, a nearly optimal feasible solution is sufficient.

Autonomous field machines or robots will come, sooner or later. The new issues for autonomous operation are safety, detection of failures, recovering after failures, and automatic refilling or emptying. As a human driver no longer operates the machine, automatic path planning is also needed, the robot has to find a route to execute the task. An optimal solution would be perfect, but a valid solution near optimal would be sufficient in most cases.

In order to be autonomous, a mobile robot has to know or solve four things: what is the task to do, what is the way to complete it, what is already known and what is the position related to known

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(Murphy, 2000). In agricultural applications the task is usually given by a human operator. Also the last two are more or less solved, because fields are mapped environment and accurate positioning devices are on the market. So the most difficult part in agricultural robot applications to be solved by artificial intelligence is mission planning. Path planning is one of the key tasks in mission planning. (Reid 2004).

Roboticists understand path planning as an algorithm that has to find a path from place A to place B so that no collisions with obstacles occur and the path is optimal with respect to a certain measure, for example traveling in minimum time or using minimum energy. In robotics path planning has been divided into two classes, to qualitative and quantitative navigation. In qualitative navigation the environment is structured so that the robot can identify landmarks and navigate using them to follow a route. In quantitative or metric navigation an exact map describes the world and it is not dependent on viewpoint. (Murphy, 2000)

In agricultural robotics the task is usually to cover the whole field, not only going from point A to point B. This kind of path planning is so different from traditional robot path planning that the algorithms are not directly suitable. Similar applications are demining, painting, mowing, mapping unknown environments etc. This kind of autonomous applications are so new (or coming) that need for this kind of path planning has appeared lately.

In Gray (2001), the orchard tractor navigation development was reported. Orchards are not open fields, trees form blocks in which the navigation is one problem to be solved and the whole mission is another. In Sorensen et al. (2004) a method for optimizing the vehicle route by defining the field nodes as a graph and formulating it as the Chinese Postman Problem. In Stoll (2003) the idea of dividing the field into subfields based on the longest side of the field or the longest segment of a field polygon. Acar et al. (2002) have introduced the use of cellular decompositions not only for path planning between two points, but also for coverage of free space, various patterns for decomposition are presented. Choset (2001) makes a survey of coverage path planning algorithms and classifies the algorithms to three classes: approximate, semi-approximate and exact. As a conclusion it may be said that the path planning of coverage type task is still under research and a general usable optimal and provable algorithm has not been developed yet, so there is space and need for further research of path planning. In this paper, an enchanced version of split and merge approach using straight driving lines is presented. Earlier version was presented by Oksanen et al. (2005).

PLANNING

The shape and size of fields varies a lot, especially in Finland fields are usually bounded by other terrain types, like forests, lakes, rocky terrain etc., and shapes are far from orthogonal and convex. If the field is convex and it does not contain any obstacles, path planning for agricultural tasks is quite simple, and only the main driving direction has to be found. The whole field is driven in that direction except headlands if needed. The selection of the main driving direction on the basis the longest edge of field has been a rule of thumb for farmers. Here this rule of thumb based on common sense has been dismissed and it will be checked if the result is still the same.

If the field is nonconvex which means that it has "bays", finding the optimal solution is hard. One possibility to solve the problem is to use split and merge approach for segmentation used in computer vision. The field is split into simple shaped subfields which are convex or near convex, an optimal solution is found for driving in the subfields and finally the solutions are combined. If the shape of a subfield is for example rectangular, finding the optimal driving strategy is pretty simple, even if not trivial. The drawback of this method is that the output, the driving route, is not necessarily a globally optimal solution, but suboptimal.

For some environment and some operations there are limitations for driving direction. For example the underdrainage system made based on height variation limits the ploughing directions, for certain soil types. Also the driving direction in previous operation may limit the driving direction, or more generally the chain of field operations. For example in tilling it may be suggested not to drive in the same direction as the field is ploughed. Another case when driving directions may be wanted to limit is a series of small permanent obstacles and wide working machine, like electric poles and sprayer. Then in the surroundings of electric line it may not be suitable to drive in directions that differ from the direction of electric line only a little bit.

Here it is assumed that the layout of the environment (field) is known. This can be assumed because fields are not changing over the years and the mapping is made, at least in Finland. The requirements for a good coverage path planning algorithm are: suitability for all kind of fields, for all kind of machines, and efficient enough in order to be solved in reasonable time.

This paper concentrates on the higher level algorithm to divide a complex shaped field into simple subfields in which the route planning is easy to do. The algorithm is suitable for all kind of crop farming machines where the task is to do some action in all places in the field exactly once.

Definitions

Certain type definitions have been set. The field is considered as an uniform 2D region which may contain obstacles. An *exterior polygon* describes the field outer boundaries and *interior polygons* describe the obstacles. *Vertices* are corner points of the polygon. *Edges* are line segments that connect vertices.

A *trapezoid* is an quadrangle which has two opposite parallel sides. A *triangle* is a special case of a trapezoid. A *block* is a polygon which is constructed by merging two or more trapezoids in their parallel and equal sides – in block two edges are parallel. *Headland* is a region in which the machine is to be turned. *Prohibited region* is a region which is a part of field where certain driving directions are prohibited.

Objective

The objective is to divide a complicated field into subfields. The algorithm searches first largest or most efficiently driven subfields, removes them from the original field and keeps finding subfields until the whole field is computed. In search of each subfield, the optimal driving direction is determined. In each step the field is split into trapezoids, the trapezoids are merged to larger blocks and the selection is made using certain criterion which takes into consideration the area and the route length of block and the efficiency of driving.

ALGORITHM

Splitting

Crop farming machines have certain working width, which usually remains constant. The requirements for best efficiency and quality are: the driving lines are exactly side by side, no gaps, no overlapping and the turning in headlands is made in minimum time. Parallel swathing assistants or light bars or autopilots help human driver to keep the machine in lane.

It has been assumed that the driving lines should be side by side and parallel to each other in order to be a good strategy. Due to that assumption, trapezoid has been selected as a prototype of the shape. Trapezoid has two opposite sides parallel corresponding to the driving direction and the other sides correspond to the edge of the field or the headland.

In this algorithm the field is split into trapezoids, this belongs to the set of exact cellular decompositions (Latombe 1991). All vertices of the exterior polygon are projected at given direction to all sides and trapezoids are detected. If the field contains obstacles, the interior polygon nodes are also projected to all sides of the polygons. An example of triangulation is presented in Figure 1. In the field on the left the number of trapezoids is 11 and in the field on the right the number is 18.

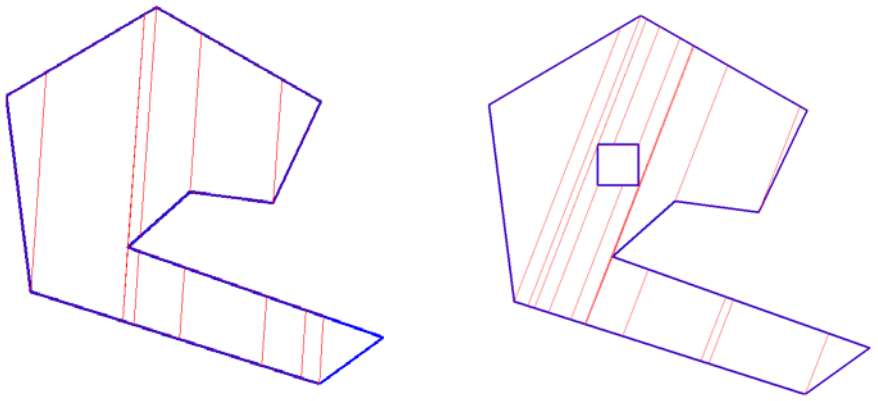

Figure 1. Two examples of triangulation.

Merging

After splitting the field into trapezoids, the next step is to combine them as far as possible. The requirement is that two trapezoids have to have exactly matching sides and the angle of ending sides is not too steep. The second requirement prevents combining trapezoids which are far from rectangular shape and should be handled in later phases separately. The minimum angle between matching side and ending side is set to 20 degrees (90 degrees means right angle). The example of merging trapezoids is presented in Figure 2.

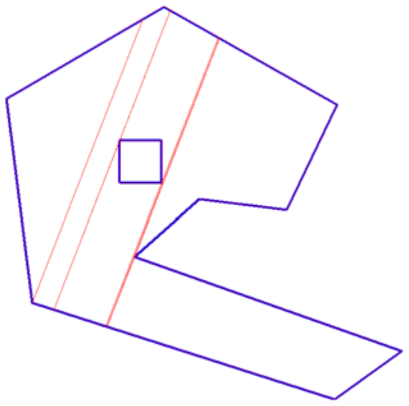

Figure 2. Merged trapezoids.

Selection criterion

The idea is that the regions which are most efficient to handle are driven first and the same algorithm is applied iteratively for the rest until the whole field is handled. The region to be selected in each step is a block, the best one of them has to be selected.

The area of the block, the distance of route fitting inside the block and the efficiency of driving are variables in selection criterion. The area is simply the area of the block. The distance is calculated using the working width information and the headland width is subtracted from that. The distance corresponds to the distance that can be driven at normal driving speed with operational part of machine working. The time consumed in the block is estimated from the distance calculated previously and the time spent in headlands is added. The estimate of turning time in certain headland angle can be calculated for example using optimal control techniques (Oksanen et al. 2004) or by splines (Noguchi et al. 2001). In perpendicular headlands (compared to driving direction) the quality is best (minimum overlapping in headlands).

In practice efficiency is the primary variable which should be maximized, but this leads easily to a situation where narrow and long blocks are selected first. That leads to an unwanted combined solution. Therefore the other two measures are needed too. All the measures (area, distance, efficiency) are normalized and the cost is a weighted sum of these. Currently the tuned weights are: efficiency 65 %, area 15 % and distance 20 % and these are used in the results below.

If some subfields are already selected, a bonus is added to the calculated cost in the directions of them. This prevents adjacent subfield directions not to differ from each other by small angles only. With most cropping machines, a small correction in direction leads to inefficiency and to quality loss.

Search of the driving direction

Splitting into trapezoids and merging them to blocks is made in certain direction. However, the direction is not known and it has to be solved. The characteristics of the blocks are not changing smoothly when the direction is changed in infinitesimal steps, so the cost function of search is not smooth. This means that all possible directions should be gone through (between 0 and 180 degrees) and it takes a lot of calculation time. The following heuristics have been used.

The search algorithm is as follows:

1. Cost is calculated in 6 directions: 0, 30, 60, 90, 120 and 150 degrees.
2. The three best directions are selected, others are dropped
3. The step size in direction angle of search is divided by two
4. New search directions are added to the both sides of the three best directions
5. Cost is calculated in directions which are not yet calculated
6. If the goal resolution is reached, exit, otherwise go to step 2

After 5 iterations, the resolution is below one degree which has been found to be sufficient.

This heuristic search algorithm was tested with a random set of real fields and the solution was compared to brute-force solution with the same resolution. The result was that over 97 percent of the solutions matched and only less than one percent of the solutions were far from the global maximum.

Headlands

As described above, the headland width is reduced from the main driving lines when calculating the efficiency. In this way the solution will be correct, but in some cases a headland is not needed. If the direction of blocks after first iteration vary from each other, it is evident that one end of block is common to the parallel side of the other block and generally then the headland is not needed. The other case when headland is not needed is a block which has very steep headland angle e.g. below 15 degrees (90 degrees means again right angle), then the headland can be driven by bending the driving line. The number of swaths needed in headland is input variable for algorithm.

Prohibited driving directions

As mentioned above, for some environments and some operations there are limitations for the driving direction. This can be formulated to this path planning algorithm by defining a prohibited region, in which range of prohibited driving directions are set in degrees. If the set of prohibited driving directions is not uniform, multiple prohibited regions may be used.

In the algorithm the prohibited regions are taken into account in split phase. If the current search angle is in the angle range of the prohibited region, the prohibited region is handled as an obstacle or interior polygon. After selection, in removing phase, the prohibited regions are cropped if needed. It is required that prohibited regions are inside the field region.

TEST RESULTS

Previously (Oksanen et al. 2005) the test results with 1500 real fields were presented. The conclusion from those tests is that this algorithm works nicely for fields with straight edges. The solutions for fields with curved edges are valid, but not so efficient. Here is presented latest results.

Automatic determination of headlands was developed. In the figures below, the headlands are drawn with blue color, and the main swaths are drawn with green. In Figure 3 a H-shaped field is presented with the solution. At first the algorithm has found two long vertical blocks on each side and finally the horizontal block between vertical blocks is handled. The headlands are needed only at the end of vertical blocks and they are automatically generated.

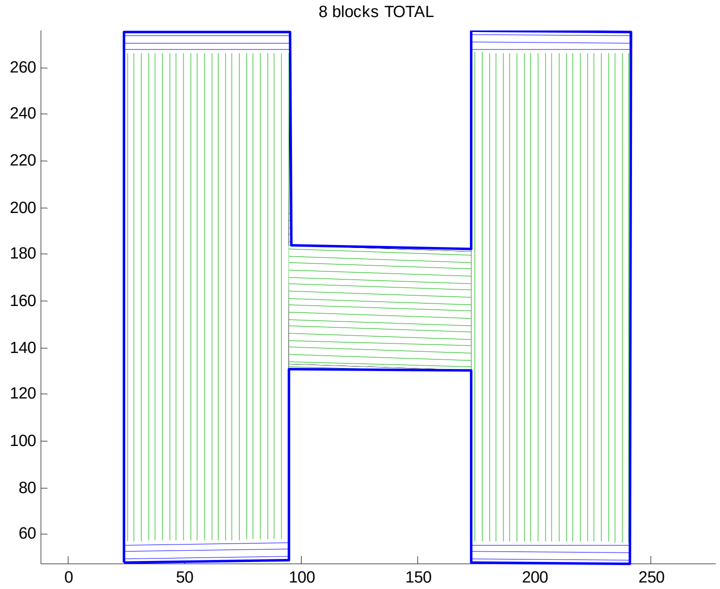

Figure 3. H-shaped field with headlands

In Figure 4 a field with many bays is shown. As it can be seen, the main driving direction was determined on the largest block in the middle. For three of four bays the same driving direction is found to be top-rated (NB: a small bonus is given to direction of neighboring blocks). The headlands are needed in most edges, but if the direction of edges is near enough to the direction of swaths (in these tests 5 degrees), the headland is not laid.

Figure 4. Field with many bays.

Prohibited regions

As described, with the prohibited regions it is possible to define impossible driving directions due to height variation and machine properties or to define unwanted, inefficient driving directions.

In Figure 5, a C-shaped field is shown. On the left is a solution without any prohibited regions. The final solution consists of 5 blocks, saving two headlands. On the right a fictional escarpment (steep slope) is inserted on one corner, this is marked with dashed line and a small red triangles, "bow", represent the forbidden driving directions. This means that the driver does not want to drive the escarpment up-down-up, but diagonal driving is allowed. Maybe his/her tractor does not have enough horsepowers to drive it uphill. However it can be seen that the solution found without the prohibited region has changed dramatically. The driving direction is changed all around the field plot and headlands are required all around the field.

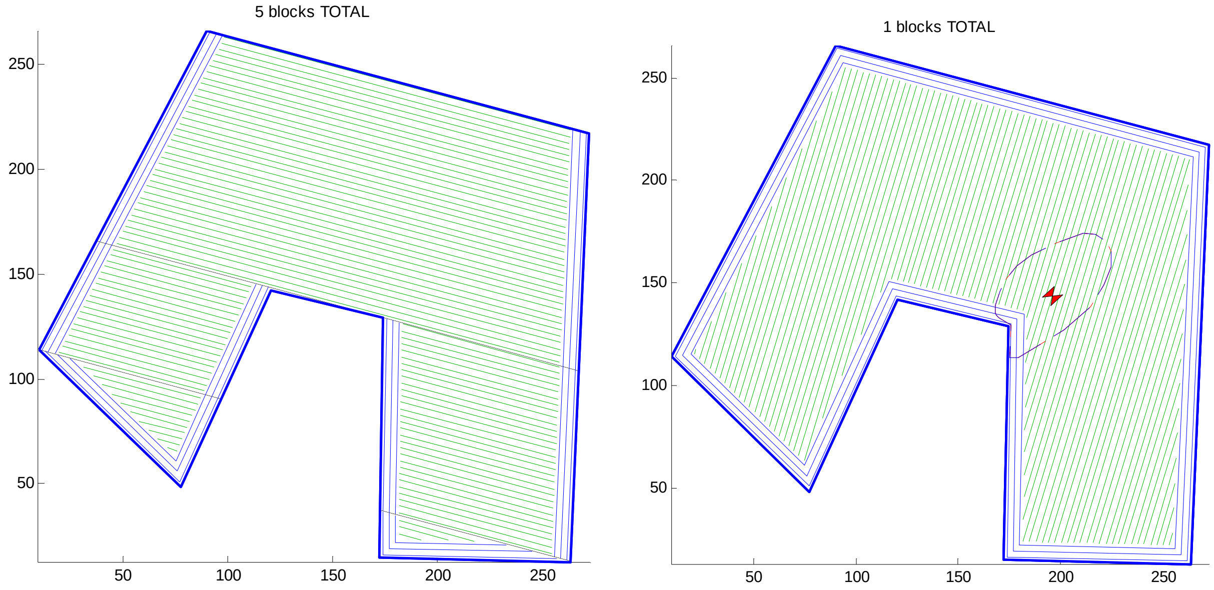

Figure 5. C-shaped field without and with prohibited regions

Lets consider another example. In Northern Europe most of the field plots are underdrained. Underdrainage is important especially in soil types which are not transmitting water easily. In certain field operations, like in ploughing it is not recommended to drive in the same direction as the pipes are laid; ploughed furrow is also kind of "pipe". When the furrows and pipes cross, the effect of drainage is at its best. In Figure 6 a field with underdrainage system is presented. A bold blue dashed line represent the collector pipe in the drainage system and blue lines are lateral pipes. Two prohibited regions are marked with red dashed lines and red "bows" are marking the forbidden driving direction range.

In Figure 7, on the left the solution of algorithm without taking underdrainage into account is presented and on the right it is considered. In both cases one dominant driving direction exists, but the right one fulfills the requirement of prohibited region. Actually the efficiency is almost the same in both cases, in simulation the right one is only 0,2% worse than the left one, if using total driving time as a measure. Naturally this fact applies only for this particular field.

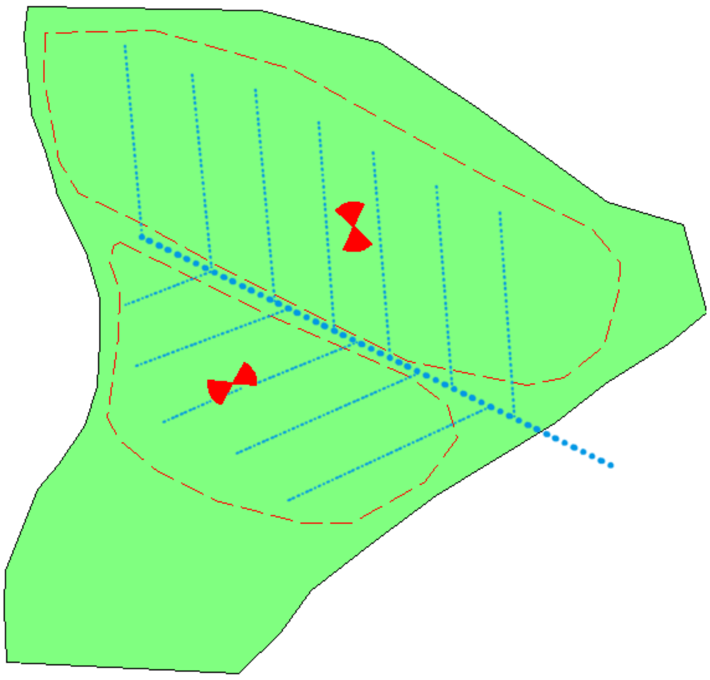

Figure 6. Field with underdrainage system

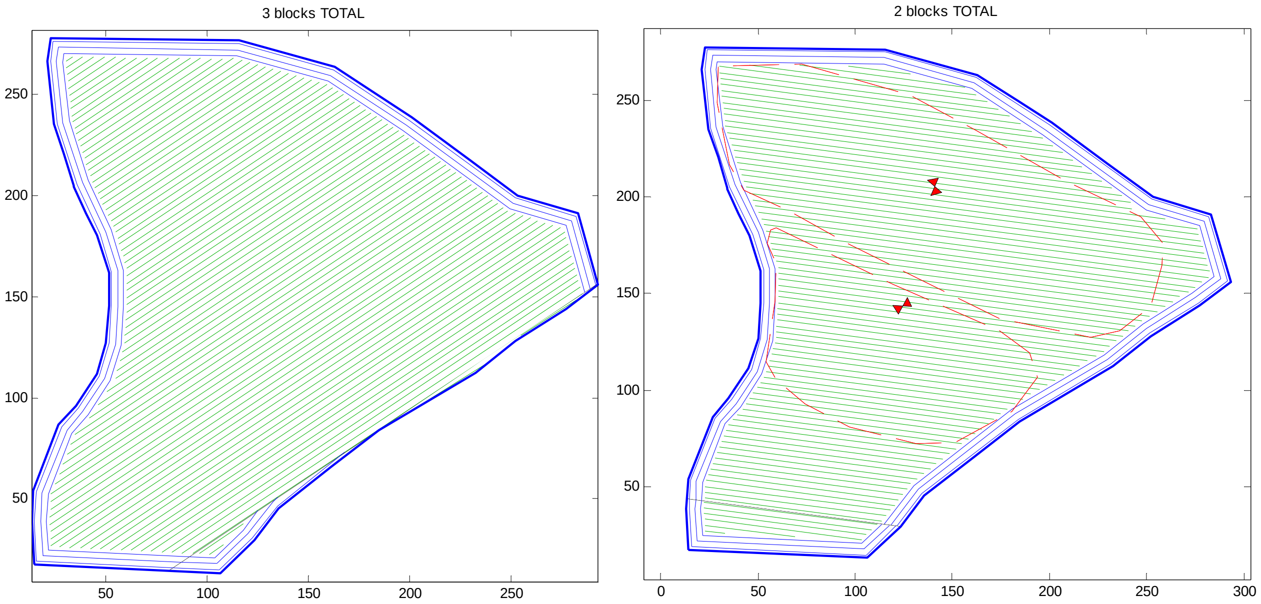

Figure 7. Solution without and with underdrainage

CONCLUSION

Path planning for robots working in fields is not yet solved. Various algorithms for path planning have been introduced, but they are still more like a collection of algorithms.

In this paper an algorithm for dividing a field into subfields is presented. The shape of a subfield is simple, so it can be driven using parallel swathing techniques. The algorithm relies on splitting the field into trapezoids, merging them to larger blocks, using search algorithm select the best driving direction and recursing the search until the whole field has been divided. The algorithm belongs to the set of exact cellular decompositions. Trapezoidal decomposition has been utilized as a part in the algorithm. Algorithm can solve the routes for any field, with any number of obstacles and any kind of shape.

In the latest version the headlands are automatically generated where needed. With prohibited regions the previous operations, underdrains and steep gradients can be taken into account. In prohibited regions certain driving directions are marked prohibited.

One drawback of the algorithm is that it only can use straight driving lines. Some fields do not have straight boundaries. Especially in fields which are narrow, long and curved, the solution is far from optimal. Refilling or emptying of the machine should be included in path planning. A general usable coverage path planning algorithm should be able to adapt to agricultural task specific requirements.

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