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Path planning algorithm for field traffic

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Abstract. *For autonomous field robots path planning is needed for automatic operation. In robotics path planning usually means that an algorithm has to find a path from place A to place B in order to avoid collisions with obstacles. In agricultural robotics, the task is usually to cover the whole field, not only going from point A to point B. The shape and size of fields varies a lot, especially in Finland fields are usually small, bounded by other terrain types, e.g. lakes or forests, and shapes are far from orthogonal and convex. A good path planning algorithm can solve the problem for any kind of field. In this paper the path planning problem is divided into two levels. In the higher level the complex shaped field is split into smaller parts and in the lower level the path is planned to smaller parts separately. 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 trapetzoidal split, merge and search. The input to the algorithm is the boundary of the field as polygons both interior and exterior, plus the main vehicle parameters. The output of the algorithm are a collection of subfield, which can be driven in parallel driving lines.*

Keywords. Autonomous robots, path planning, motion planning, agricultural fields, coverage, algorithm.

Introduction

Tractors and other 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 his/her own experience. In family size farms the strategy is based mostly on experience, 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 (Murphy, 2000). In agricultural applications the first is usually given by human operator, the task. 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 application artificial intelligence to be solved is the path planning, how to drive the field.

Roboticists understand the 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 travelling in minimum time. 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 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 the 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.

The planning task

The shape and size of fields varies a lot, especially in Finland fields are usually bounded by other terrain types, like forests, lakes 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 task is quite simple. 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 and an optimal solution is found for driving in subfields and finally combine them. 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 globally optimal solution, but suboptimal.

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 cropping machines where the task is to do some action in all places in the field exactly one time.

Definition of types

Certain type definitions have been set. The field is considered as an uniform 2D area which may contain obstacles. An exterior polygon describes the field outer boundaries and interior polygons describe the obstacles. 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.

Field to subfields

The target 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

A crop farming machines have a certain work width, which usually that remains constant. The best efficiency and quality is reached if 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 lightbars 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.

The field is split into trapezoids, this can be defined as an exact cellular decomposition (Latombe 1991). All nodes 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 polygons. The 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.

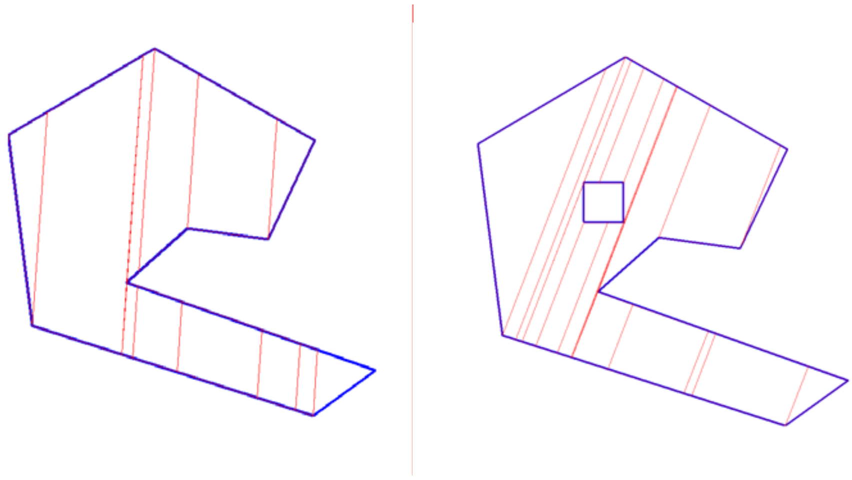

Figure 1. Two examples of triangulation.

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 square corner). The example of merging trapezoids is presented in figure 2.

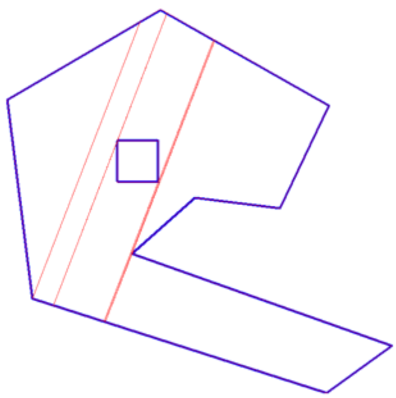

Figure 2. Merged trapezoids.

Selection criterion

After the blocks have been constructed, 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 taken into consideration. The area is simply the area of the block. The distance is calculated using the toolwidth information and the headland width is substracted from that. The distance corresponds to the distance that can be driven at normal driving speed. The time consumed in the block is estimated from the distance calculated and using normal driving speed information 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). In normal headlands (compared to driving direction) the quality is best (minimum overlapping in headlands).

Practically the efficiency is the one which is wanted to be maximized, but that leads easily to situation that narrow long stripes are selected at first and that leads unwanted complete solution. Therefore the other two measures are needed also. All the measures (area, distance, efficiency) are normalized and the cost is a weighted sum of those. Currently the tuned weights are: efficiency 65%, area 15% and distance 20%.

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

Search 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. Here 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 halved
4. New search directions are added to the both sides of the three best directions
5. Cost is calculated to directions which are not yet calculated
6. If the goal resolution is reached, exit, otherwise go to step 2

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

This heuristic search algorithm was tested with random 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.

Test results

A set of Finnish fields was used to test the algorithm. The set was about 1500 fields and the average area was 3.87 hectares. Five percent of the fields were convex without obstacles and about thirty percent were near convex. Thirteen percent of the fields contained obstacles.

In test fields the machine specific parameters were: toolwidth 2.5 m, headland width 7.5 m and the driving speed 10 km/h.

The algorithm was able to find a solution for all fields.

All the solutions were checked by hand and it can be said that almost all of them are valid, but it is difficult to say how near of far they are from optimal. Problems occurred when the field contained many small obstacles, which resulted in a solution which was much different from the solution without obstacles. In future research the minimum size of an obstacle in higher level splitting has to be considered.

The number of subfields varied from 1 to 67. The histogram of number of subfields is presented in figure 3. When the number of subfields is low the number tends to be odd. Generally it can be said that the smaller the number of subfields is, the better the whole solution is.

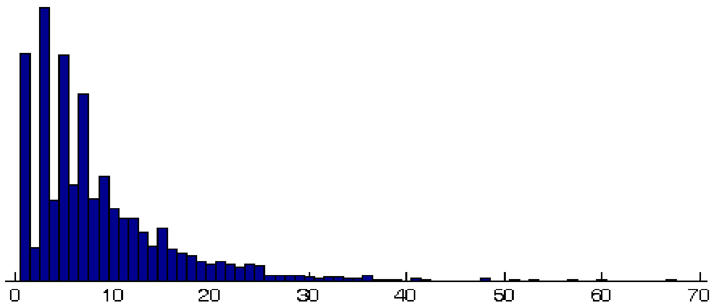

Figure 3. Number of subfields in histogram

It is difficult to measure the overall optimality of the solutions as an optimal solutions are not available. In the future the solutions will be analyzed by professional drivers and experts.

It can be said that for convex fields without any obstacles, the solution is optimal along with the criterion used because only one subfield exists. It was found that if a convex field has a clear longest edge, the direction given by the algorithm was congruent with the longest edge of the field. Solutions for some convex or near convex field are presented in figure 4. In the plot on the left the driving direction is congruent with the longest edge of the field. In the plot on the right the field is not convex and there exists no clear longest edge, but the algorithm has found a solution which can be assumed to be a good one.

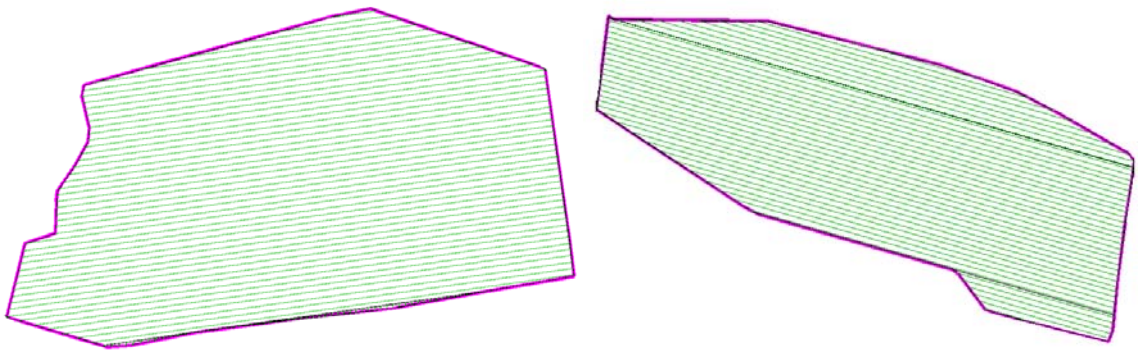

Figure 4. Easy fields

If the field is not convex nor near convex, but it has clear corners and clear straight edges, the solution is easily found. One such field is illustrated in figure 5 (left plot). The plot on the right in figure 5 is near convex, but it has an obstacle in it, the solution mainly follows the longest and the second longest edges.

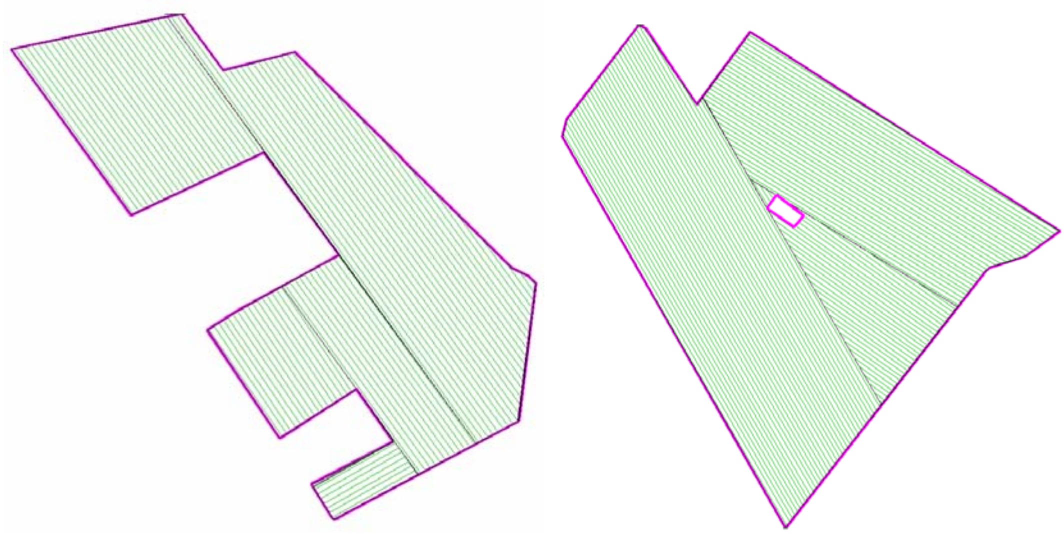

Figure 5. Typical fields

In such fields which are narrow, long and curved without any clear straight edge, the solution optimality is not clear. If the machine allows curved lanes, then it may be sensible to follow the edges of the field. In Finland this kind of field shapes are not rare, because some of the fields are limited by nature like forests, rocks or lakes, not by the fields of the neighbor. Two examples of curve-edged fields and the solutions are presented in figure 6.

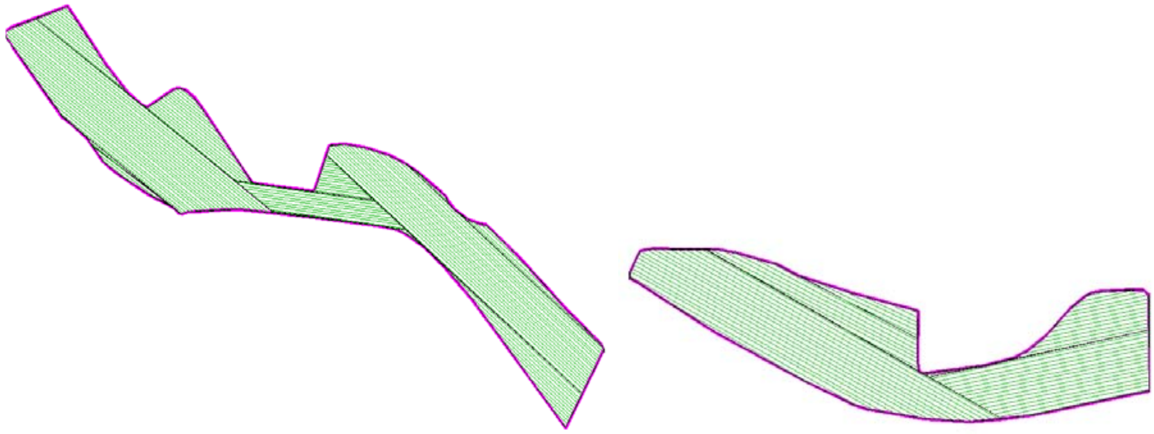

Figure 6. Curved fields

Then there exist some complexly shaped fields in the test data. Those fields contain many "islands" and "bays" and the driving takes a lot of extra time, regardless of the path. The solutions for two different complexly shaped fields are presented in figures 7 and 8.

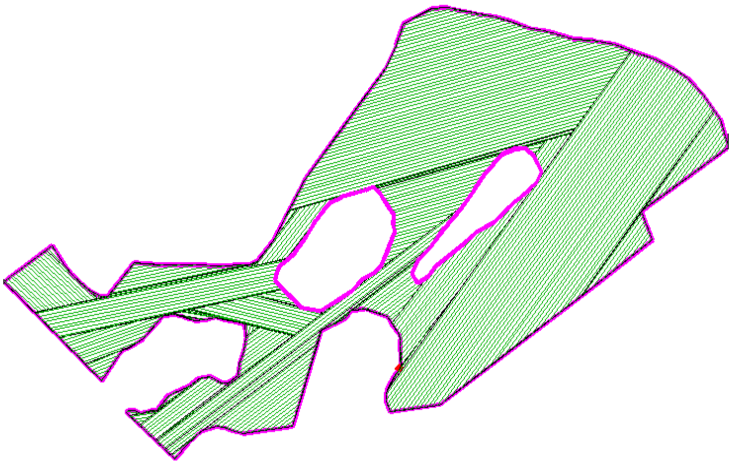

Figure 7. Complexly shaped field

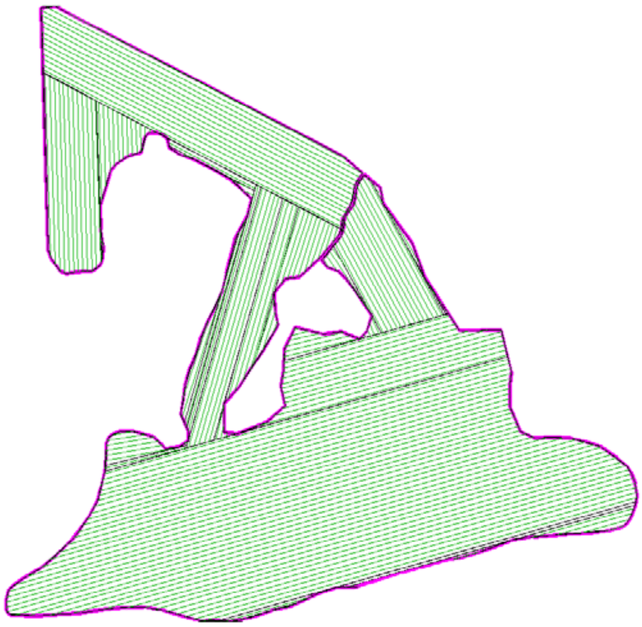

Figure 8. Complexly shaped field

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 can be classified into exact cellular decomposition. Trapezoidal decomposition (a common form of exact cellular decomposition) has been utilized as a part in the algorithm.

A set of Finnish fields have been used to test the algorithm. The algorithm can find a solution for all fields. It is difficult to measure the overall optimality of the solutions. Human evaluation of the results will be made in the future.

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. This drawback should be resolved in the future research. Currently the algorithm takes the headlands into consideration in the criterion but they are not considered as their own blocks in the result. This will be corrected in future development.

After the blocks have been constructed, the next step is to connect them as one route. One possibility to connect them optimally is to formulate the problem as a Rural Postman Problem, which is one modification of Chinese Postman Problem. This will be tried in future research.

In some agricultural tasks there are also some limitations for selecting the driving direction, for example in plowing the direction of underdrains has to be considered. Also refilling or emptying of the machine should be included in path planning. General usable coverage path planning algorithm should be able to adapt to agricultural task specific requirements.

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