58. Optimizing agricultural coverage path to minimize soil compaction

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Abstract

The Coverage Path Planning (CPP) problem is the optimization problem of finding the best path that covers a complete area. In agriculture, the coverage path defines the path that the tractor follows, which is directly related with soil compaction. Despite the consequences of soil compaction, using the disturbed soil as a cost function for the CPP problem has been little explored. This paper compares three methods to compute the disturbed soil for wheeled and caterpillar tracked vehicles. The methods are tested on simulation and compared visually on a real field. The experiments show that the presented methods can compute the disturbed soil area on a 3 km path accurately in less than 12 s.

Keywords: coverage path planning (CPP), soil compaction, unmanned ground vehicle (UGV), computational geometry, cost function

Introduction

Soil compaction is a major problem in agriculture, as it can significantly reduce the crop growth and yield (Doran, 2002). To minimize soil compaction caused by machinery, techniques of precision agriculture, such as controlled traffic farming (CTF) may be utilized (Antille *et al.*, 2019). CTF is characterized by having defined lanes where the machinery traverses the field, called swaths (De Bruin *et al.*, 2014). Those swaths, and the path to go from one to another, need to be planned and optimized before operating on the field (Oksanen and Visala, 2009). This optimization problem is called Coverage Path Planning problem (CPP).

To compare between coverage paths and decide which is better, a cost function needs to be defined. Although common cost functions, such as the path length or the number of turns (Jin, 2009), are used to minimize the task time and the soil damage, the reduction on the soil compaction is a side effect of shorter paths.

Accepting that measuring soil compaction is a complex task, several soil models have been explored (Keller *et al.*, 2007; Van den Akker, 2004). Although simple soil models, such as the Soil Contact Model, can be run on real-time simulations (Tasora *et al.*, 2019), computing the total soil compacted over a long path would require waiting until the tractor completed the path at normal speed. If it was used as a cost function, each evaluation would take several hours. Those time durations limit the optimization flow to only a few cost function evaluations. Therefore, it is required to define computationally cheap cost functions that assess the damaged soil.

This paper presents and compares three methods to compute efficiently the disturbed soil over a coverage path: the Buffering, the Wheel-Trace and the Track-Trace methods.

The objective of this research is to develop a cost function that can quantify the soil compaction caused by a tractor following a specific coverage path. The outcome of this study has the potential to reduce machine-caused soil damage and thus improve field yields.

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Materials and methods

Fields2Cover library

Fields2Cover (Mier *et al.*, 2022) is an open-source library for agricultural coverage path planning. The library contains four modules: headland generator, swath generator, route planner and path planner. Each module has its own cost functions and novel cost functions can be added. In this paper, Fields2Cover was utilised to compute the path that connect previously mentioned swaths, using continuous-curvature Dubin's curves (Fraichard and Scheuer, 2004). Constraints as the minimum turning radius (3 m) or the maximum curvature change (0.2 m^{-2}) are set to reduce the soil damage and to make the path feasible.

Cost functions

This paper compares three alternative methods, the Buffering, the Wheel-Trace and the Track-Trace methods, to assess the disturbed soil area for a robot with wheels or caterpillar tracks. All the methods have two steps:

1. Obtain the path of each of the wheels/tracks independently.
2. Determine the areas traversed by the individual wheels and combine these areas over the entire path.

The first step is common for all the methods. Caterpillar tracks are considered as multiple wheels on the same track. The position and angle of the robot on the path and the position of the wheel on the robot are used to obtain the path of the wheel with respect to the world.

The Buffering method assumes that wheels are semi-spheres where the plane that crosses the centre is the base. The soil disturbed is the same as the wheel path buffered by half of the width of the wheel. In case of tracks, several wheels are placed evenly instead of the track and the wheel tracks are combined to create the soil disturbed area.

In the Wheel-Trace method, each wheel is considered as a cylinder with a line of contact parallel to the rotation axis, and perpendicular to the direction of the wheel. The wheel line of each timestamp of the wheel path is connected to the next timestamp to compute the area of the cost function. Tracks, as in the first method, are substituted by several evenly distributed wheels.

The Track-Trace method simplifies tracks to two lines perpendicular to the direction of the robot. Those lines are created at the beginning and at the end of the tracks for each timestamp of the path. The disturbed soil area between two timestamps, *A* and *B*, is created combining: the area of the tracks at *A* [*A1, A2, A3, A4*], the area covered by the back part of the track [*A3, A4, B4, B3*], and, if going forward, the area covered on a right turn [*B3, A1, B1, B2, B4*] and left turn [*B3, A1, B2, A2, B4*] depicted in Figure 1.

Experiments

The methods are compared first on simulation. Then, one of the methods is select to be compared visually with real data. The experiments were carried out on a ploughed field in Oirlo, the Netherlands (X:296615, Y:5711009, ETRS89, UTM32). The average temperature of the week before the experiments was -8 °C. Due to the weather conditions, soil was dry and frozen, reducing the slippage. The field (Figure 2) has been covered with 72 swaths. A 12-swaths pattern has been used to test turns that have an entrance angle into the headland of 0, 15, 30, 45, -15, -30 and -45°. Except with -45 and 45°, where turns are made only to continuous swaths, the other cases turns are generated for the two nearest swaths. The total path has a length of 2,945.0 m, the area of the total field is 1.94 ha and the area of the covered area is 0.49 ha. The same field and path are used on all the experiments. To compare between the real and simulated data, a robot was used to follow the path on the ploughed field. The tracks were photographed using a drone. The third method was used to compute the soil disturbed area. The drone photo and the soil disturbed area were overlaid to estimate the accuracy of the method.

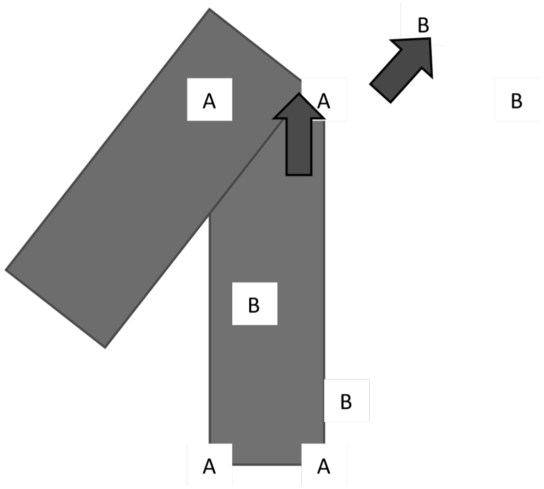

Figure 1. Diagram of a track moving between timestamps *A* and *B*, from the position [*A1, A2, A3, A4*] to [*B1, B2, B3, B4*]. The diagram corresponds to a forward right turn.

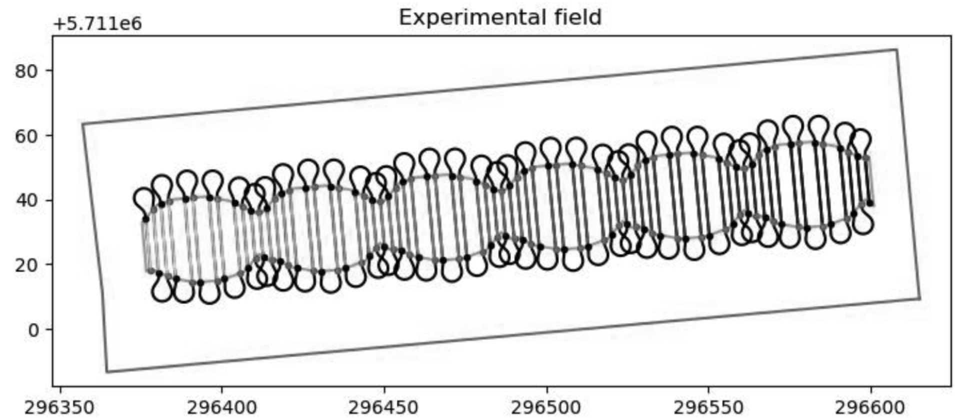

Figure 2. Experimental field area. The covered area is in orange. Swaths are drawn from green to dark green according to the order traversed. The path is on back. Axis are the coordinate values on ETRS89 and UTM32.

The values compared on the experiments are the disturbed soil area and the computation time. The computation time is the time that is required to compute the disturbed soil area, once the path is already known. Computational times have been measured 10 times for each method on the same path. The computer employed to measure times is a Quad core Intel Core i7-7700HQ with 6,144 KB cache and 3,800 MHz maximum clock speed.

Agbot

The robot employed for the experiment was the AgBot 5.115T2, from AgXeed B. V., Oirlo (the Netherlands) (Figure 3). This vehicle is a differential robot with two 0.6 m-width rubber-band tracks with 6 wheels each. A path (position, angle and velocity) is provided to the AgBot using Protobuf protocol. GNSS (Global Navigation Satellite System) and a PID-controller are used to follow the path.

Figure 3. AgBot 5.115T2.

Results and discussion

Method comparison

According to the Table 1, the Track-Trace method is the fastest, followed by the Buffering method. Moreover, the Buffering method returned a larger area than the other methods, owing to the semi-spherical wheel assumption when buffering the path. This method computes the soil disturbed by a wheel in one function. Therefore, it is challenging to assess the areas that are covered several times. Finally, the Wheel-Trace method is slower compared to Track-Trace method. However, more information about the wheels of the tracks is obtained. In both latter methods, the soil disturbed several times can be found.

Table 1. Comparison of the proposed methods.

Method	Soil disturbed (m^2)	Avg. computation time (s)	Advantage	Disadvantage
1. Buffering method	3,342.87	8.2003	Easy to understand and fast to compute	More soil disturbed computed. Not possible to compute track steps or backward movement.
2. Wheel-Trace method	3,306.18	11.4152	Precise area computed if number of wheels in track is high	Depends on the number of wheels on the tracks.
3. Track-Trace method	3,311.33	7.8666	Precise area computed	Cannot classify the soil disturbed by the wheel of the track.

Comparison between track-trace method and the experiments

The disturbed soil area according to method 3 is remarkably similar to the track mark of the AgBot in the field experiment (Figure 4). As previously mentioned, the soil was frozen, which reduced the soil slippage. Thanks to that, the similarities between computed and real track marks are strong. Unfortunately, some parts of the computed disturbed soil differ from the observed ones, which could be caused by an unprecise calibration between the centre of rotation of the robot and the tracks. As the vehicle changes the rotation point according to the soil stability, computing it is a complex problem. Despite of that, the third method, as well as the other methods which provided similar outputs, returned solutions that closely match the soil disturbed by the AgBot.

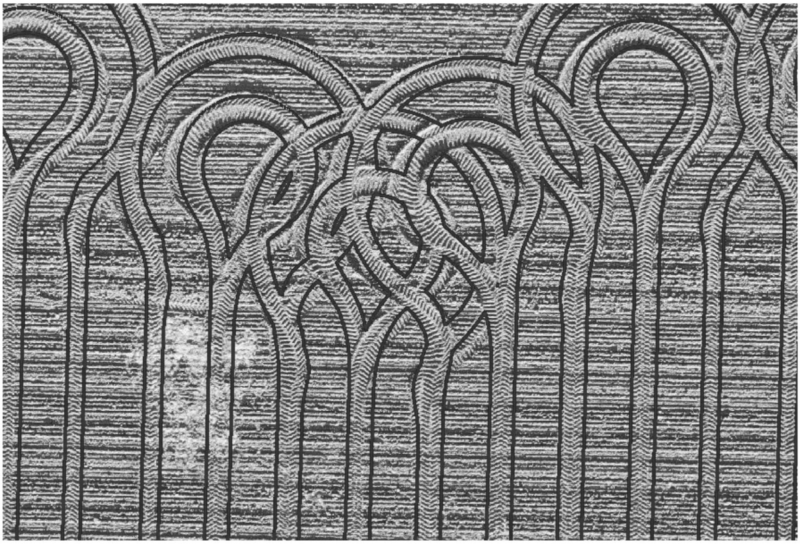

Figure 4. A photo of the track mark left by the AgBot during the experiments. In blue there is the disturbed soil area computed using the Track-step method.

Conclusions

This paper presents three methods to compute the soil disturbance of a coverage path. While other approaches to reduce the soil compaction when planning the coverage path minimize the path length, as a simplification, or use computationally expensive models, the methods explored provide an accurate approximation of the soil disturbed. Each method has advantages over the others, despite computing similar results (the percentage of the intersected area of all methods over the result of one of them is >98%).

Due to these methods being computationally cheap, the inclusion of the soil disturbed as a cost function on the route planning is feasible.

Although the results were promising, further tests should be considered to confirm the outcome of these methods and research about their limitations.

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