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Path Planning for ground robots in agriculture: a short review

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***Abstract*—The world's population is estimated to reach nine billion people by the year 2050, which indicates that agricultural productivity must increase sustainably. The mechanisation and automatisation of agricultural tasks is an essential step to face population growth. Ground robots have been developed along the last decade for several agricultural applications, being, the autonomous and safe navigation one of the hardest challenge in this development. Moving autonomously, a mobile platform involves different tasks, such as localisation, mapping, motion control, and path planning, a crucial step for autonomous operations. This article performs a survey of different applications for path planning techniques applied to various agricultural contexts. This paper analyses different agricultural applications and details about the employed path planning method. The conclusion indicates that path planning has been successfully applied to agrarian robots for field coverage and point-to-point navigation, being that coverage path planning is slightly more advanced in this field.**

***Index Terms*—Autonomous navigation, Path Planning, agricultural robotics, heuristic, survey.**

I. INTRODUCTION

Agriculture is a critical sector of the global economy. This activity was adapted along years to fulfil the needs of the world's population, which has duplicated in the last 50 years [1]. Several studies predict the continued growth of the world population, expecting to reach nine billion people by the year 2050, a 60% increase. Further, the prediction indicates an increment of people living in urban areas and a decrease in the ratio between working people and retired people [2]. Besides, there has been a substantial decrease in human resources for agricultural labour [3], [4]. This data indicates that the world's agriculture productivity must increase sustainably, and more independent of handcraft work with the automatisation and optimisation of agricultural tasks. The technology was introduced to agriculture more than one century ago, with the first tractor presented in 1913. Nowadays, mechanical technology has had a considerable evolution, with a considerable amount of commercial technology available [5]. This evolution increased agricultural productivity and reduced the necessary amount of human labour in agriculture. However, this may not be enough to sustain the world's demand for future years. There are several studies performed since the 1990s to improve the production efficiency, which originated the concept of "precision agriculture", a farm management notion based on the observation, measurement, and actuation to the variability in the crops, to optimise the returns while preserving resources [6].

The strategic European research agenda for robotics [7] states that robotic platforms will improve agriculture efficiency. However, despite the increase of this area in the research domain [8], few commercial solutions are available [9]. Multiple works applied automation solutions for different agricultural tasks such as planting, harvesting, monitoring, spraying, and pruning. For all of these processes, the autonomous robot navigation is essential. This step consists of four requirements known as localisation, mapping, motion control, and path planning, a necessary part of the autonomous robot navigation. Path planning of a robot consists of finding a sequence of translation and rotation from a starting point to a destination while avoiding obstacles in its working environment [10].

Agricultural environments place many challenges for robotic navigation. Unlike indoor environments, agrarian fields are intricate, unstructured, and fickle. The path planning strategies well suited for inside spaces may not fit in the agricultural requirements, which creates the necessity of advanced path planning strategies suited for agriculture.

The literature contains several works regarding this issue, with early works dating from 1989, where Palmer *et al.* [11] presented an issue about efficient field courses around an obstacle motivated by concerns in the farming industry. Bochtis *et al.* [12] did a review about advances in agricultural machinery, where one of the approached topics involves path planning methods for area coverage in farms. To the best of our knowledge, there is no other revision work about path planning applications in agriculture. So, this paper analyses the approaches taken along the years for path planning in several agricultural areas.

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Section II shows the methodology used for this review work. Section III presents a brief explanation of the path planning concept and its different approaches. In section IV, the found related works with path planning in agriculture are analysed. Section V presents the conclusions of this revision.

II. METHODOLOGY

The collection of the related work was performed between December 2019 and January 2020, resorting to the scientific search engine Google Scholar. The search was open to any path planning approach in the agrarian field for ground robots, and white22 papers were selected from different agricultural areas. The analysis of the related work intends to answer the following issues: i) agricultural task ii) planning approach; iii) on-line capability; iv) dynamic or static; v) path optimality; vi) geometry features; vii) optimisation criteria; viii) robot restrictions; ix) limitations; x) computational complexity and processing time; xi) real scenario tests.

III. PATH PLANNING ALGORITHMS

Based on the environment information, there are two categories of path planning algorithms, off-line and on-line. The first category is used when the robot has prior access to complete information about the environment, including static obstacles and trajectories of non-static objects. On the other hand, when this information is incomplete or not available, the robot should evaluate the path during the navigation. This second category is known as on-line path planning. A fundamental approach for formulating and solving the path planning problem is the configuration space (C-space) approach. The central idea is the representation of the robot as a single point. As the robot is reduced, the obstacles are enlarged by the size of the robot to compensate [13]. The path planning methods consist of various concepts such as potential field, sampling-based method, cell decomposition and nature-inspired algorithms as the Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), and Ant Colony Optimisation (ACO). Independently, path planning can be divided into two sub-categories: Point-to-Point Path planning and Coverage Path Planning.

A. Point-to-Point path planning

In Point-to-Point Path planning of a mobile robot, the goal consists of determining a collision-free path from a starting point to a destination point, optimising parameters like time, distance, or energy.

In potential field planners, the robot behaves as a particle immersed in a potential field, where the goal point represents an attraction potential, and the obstacles represent repulsive potentials. A common problem is the existence of local minimums, which emerges when the repulsive potential is higher than the attraction potential. This situation may prevent the robot from reaching the destination point [14].

Rapidly exploring random tree (RRT) is a known sampling-based method, which explores the path randomly. Although these planners are simple, they are not optimal and tend to generate paths with abrupt curves [15]. However, Karaman *et al.* [16] presented RRT* which converges to a near-optimal method.

The cell decomposition method decomposes the free space into small regions called cells [17]. The goal is to search for a collision-free path using the empty spaces in the cell graph [13]. Each cell contains information about its availability. Search algorithms like A* or Dijkstra are recurrent with the cell decomposition method to search for a path. When using A*, this method always generates an optimal path, according to the desired requirements. However, this approach has elevated computational complexity. Goto *et al.* [18] presented a method with A* algorithm to improve the processing time. Fernandes *et al.* [19] approach uses cell decomposition with A* to restrict the robot to its maximum turning rate.

Nature-inspired algorithms have obtained attention in the path planning field. GA, PSO, and ACO are recurrent studies targets in literature, demonstrating good performances for robot path planning. Mac *et al.* [10] details and reviews literature of these nature-inspired path planning methods.

GA is an optimisation tool based on natural genetics, which takes advantage of procedures such as natural selection, crossover, and mutation. [10] Elhoseny *et al.* [20] implemented a modified GA for path planning in a dynamic field.

PSO is a population-based algorithm like GA. However, PSO was inspired by the social behaviour of fish schooling. PSO is initialised with a set of random solutions, and then they are updated based on an optimal schema. Zhang *et al.* [21] proposes a multi-objective PSO for path planning in uncertain environments like a fire rescue mission, landmines, and enemies war field.

ACO is implemented by swarm behaviour, originated from natural ant colony functioning. The interacted communication between the ants enables them to find the shortest path between the nest and food sources. This characteristic is inherited in ACO algorithm to solve discrete optimisation problems [10]. Recently, Xiong *et al.* [22] used an ACO algorithm for path planning of multiple autonomous marine vehicles.

B. Coverage path planning

Coverage path planning (CPP) is the task of determining a path that passes overall points of an area or volume while avoiding obstacles [23]. Cao *et al.* [24] defined the following requirements for a coverage operation:

1) The robot must cover the whole area.
2) The robot must fill the region without overlapping.
3) The operations should be continuous and sequential without repetition of paths.
4) The robot must avoid all obstacles.
5) Use simple motion trajectories.
6) An “optimal” path is desired under available conditions.

However, it is not always possible to satisfy all of these requirements in complex environments. Therefore, priority consideration is required. Independently the on-line or off-line classification, these algorithms can be classified as heuristic or complete, depending on the guarantee of complete coverage of the free space [23]. Cellular decomposition is used either implicitly or explicitly by many coverage algorithms, where space is broken into simplistic regions to guarantee the coverage. These algorithms can be approximated, semi-approximated, and exact [25]. Randomisation is an approach for coverage problems, which, although far from optimal, is a low-cost solution for small dimensions robots working on confined spaces. Choset *et al.* [26] claims that the main advantage of a random approach is that no localisation sensors neither complex algorithms for path planning are required. However, this is unthinkable for agricultural field demands, as precision agricultural tasks require specific operations that cannot be fulfilled with random operations. Also, the operation costs of the platform would be significantly higher.

Exact cellular decomposition methods break the free space into simple regions (cells). The free cells are simple to cover using simple motions. For example, a zigzag pattern could cover all the free cells. Choset *et al.* [27] and Acar *et al.* [28] present approaches for path generation with exact cellular decomposition. Acar *et al.* [29] discuss coverage path planning in demining applications. This paper states an omnidirectional vehicle with two coverage algorithms: exact cellular decomposition with back-and-forth motion and a probabilistic method. Zelinsky *et al.* [30] used the conventional Wavefront algorithm to determine a coverage path. Yang *et al.* present a neural network tool for coverage path planning problems [31] for application in cleaning robots in dynamic environments. Schäfle *et al.* [32] proposed a coverage path planning using GA with energy optimisation. The ACO algorithm was the choice of Chibin *et al.* [33] to resolve a complete coverage path planning problem.

IV. Path Planning in agriculture

Path planning applications in agriculture are spread over several areas with different applications, being that we have identified a total of 22 papers for this review. From these works, 10 articles present Point-to-Point path planning approaches, while the remaining 11 papers deal with coverage path planning problems. The agricultural applications are spread over various areas such as navigation in orchards, vineyards, greenhouses, and wheat plantations. The navigation has several purposes like monitoring, precision spraying, and harvesting. However, some authors present a path planning algorithm adapted for agricultural fields and/or machines without applications to a specific task. There is not a popular path planning algorithm for agrarian purposes, with distinct approaches for each work either for 2D or 3D environments. Tables I and II present details about the works mentioned in this section, with a list of all the selected papers and short answers for the questions presented in section II.

In Point-to-Point path planning, the earliest article referred dates from 1997 and presents a GA for creating a path to an agricultural robot, considering only the restrictions imposed by the platform. [34] Then, the work of Linker *et al.*, in 2008, presents an article with a modified cell decomposition with A* algorithm for navigation in orchards, considering the roll and pitch angles imposed to the robot. The authors claim that the generated path is optimal, but some of the restrictions may generate a sub-optimal path. Recently, Santos *et al.* [35] resorted to a similar approach for safe navigation in a steep slope vineyard, where the algorithm limits the roll, pitch, and yaw angles considering the centre of mass of the robot. Some extensions of this method consider other parameters like the soil compaction and automatic recharging systems. Another work in literature uses cell decomposition with D*, which is based on A* but considers the robot dynamics. The goal is to navigate in an unknown oil palm plantation [36]. An artificial potential field planner is used for energy optimisation in an unstructured 3D terrain [37], and Mai *et al.* [38] resorts to an ACO for multi-point measurement in potato cultivation. Although cell decomposition is slightly preferred, the authors diverge in the choice of an algorithm for Point-to-Point path planning.

In coverage path planning problems, the chosen algorithms also vary in the found literature. A common goal in this area is the complete coverage of irregularly shaped terrains. So, the earliest selected work proposed, in 2006, a Hamiltonian Graph exploration to coverage irregular-shaped fields to minimise overlaps and manoeuvres [45]. While Oksanen *et al.* [25], presented in 2009, a greedy algorithm with a heuristic algorithm for coverage curve-shaped fields. Five years later, Hameed *et al.* [46] proposes a GA-based algorithm to find the optimal driving direction, which minimises the fuel consumption of an agricultural machine. Three more recent works, also propose methods for optimisation of irregular polygons with a 2D grid-based method with 3D projection with cylindrical topography optimisation [47], a robot swarm for seeding task (coverage algorithm not specified) [48] and an approach for coverage wheat areas for robot combine harvester with an N-Polygon algorithm to determine the optimum area [49]. A* and Dijkstra search in graphs are referred in three papers, to cover all the rows of a steep slope vineyard [50], the rows of hilly vineyards [51], which are similar but not so complex, and the rows of plants in greenhouses for precision polinization [52].

The authors of nine articles claim that their approach is optimal or near-optimal, while in other seven works, the authors provide a sub-optimal solution. The majority of the approaches are off-line path planners in a static environment, being that only two Point-to-Point papers [35], [36], and two coverage path planning papers [48], [52], propose an on-line solution in dynamic environments. However, less than half of the authors claim to have performed tests in a real scenario, being that only 3 Point-to-Point approaches are included in this group. Besides, some works do not even specify the robot's characteristics.

The computational complexity was analysed without any official metrics, as most of the authors did not provide enough information on this topic, not even computational requirements, and in some cases, temporal requests. In coverage path planning, some papers classify their method with non-deterministic polynomial-time (NP) complexity, which is a

TABLE I: Point-to-Point path planning applications in agriculture

Agricultural application	**Path Planning Approach**	**On-line or Off-line**	**Dynamic or Static environment**	**Optimal Path**	**Geometry Features**		**Optimisation Criteria**	**Robot Restrictions**	**Limitations**	**Tested in real scenario**	**Computational Complexity / Processing time**	**Ref.**
					2D/3D	Terrain Configuration						
Create a work path for agricultural robot	GA	Off-line	Static	No	2D	N/A	Shortest path with robot restrictions	Car-like vehicle: -maximum steer angle of 40º -maximum steer rating of 7º/s -velocity range: 0.4 - 1.2 m/s	N/A	No	Complex / 100 s	Noguchi *et al.* [34] (1997)
Orchard Navigation	Modified Cell Decomposition with A*	Off-line	Static	Yes	3D	Parallel rows and random generated obstacles	Shortest path that: -Avoids excessive roll and pitch angles; -Prevents soil compaction.	Car-like vehicle: -limited steer angle; -limited pitch and roll; -forward motion preferable;	Preference of forward motion may generate a suboptimal path. (Longer path and processing time)	No	Medium High / -average: 8 s; -best case: 1.391 s; -worst case: 24.844.	Linker *et al.* [39] (2008)
Navigation through oil palm plantation	Cell Decomposition with D* Lite	On-line	Partially dynamic	Yes	2D	Unstructured tree plantation	Shortest path	Differential robot	Robot can't exactly follow the path	Yes	Medium High / N/A	Juman *et al.* [36] (2017)
Energy optimization for battery powered agricultural robot	Artificial Potential Field	Off-line	Static	No	3D	Unstructured 3D simulated terrain without obstacles	Optimise energy consumption avoiding uphills	N/A	N/A	No	Simple / N/A	Yan *et al.* [40] [37] (2018 / 2020)
Pre-generate paths for Automatic Recharging system for robot navigation in steep slope vineyards	Modified Cell Decomposition with A*	Off-line	Static	Yes	3D	Irregular curved vine rows with high slopes at the edges	Shortest path with minimum energetic cost	Differential Robot	Algorithm may need to run for hours in the first time execution	No	Medium High / 90 min. to generate all the possible paths	Santos *et al.* [41] (2017)
Navigation in steep slope vineyards aware of soil compaction		Off-line	Static	No			Shortest path while avoiding soil compaction	- Differential robot; - Tricycle robot; - Tracks robot;	Processing time increases to avoid the compaction when several paths are generated in the same location	No	Medium High / Differential: [50, 600] ms Tricycle: [50, 400] ms Tracks: [100, 200] ms	Santos *et al.* [42] (2018)
Navigation in steep slope vineyards aware of vegetation wall distance		Off-line	Static	No			Shortest path maintaining the distance to the vegetation	Differential Robot	It is not possible to guarantee the exact distance during all the path	No	Medium High / N/A	Santos *et al.* [43] (2019)
Navigation in steep slope vineyards aware robot's centre of mass		On-line	Partially dynamic	Yes			Shortest safe path: - avoiding excessive roll and pitch angles; - Controlling orientation and limiting maximum robot turn rate;	Differential Robot: -limited pitch and roll according centre of mass; -limited maximum turn rate;	Heavy in terms of computational memory for big dimension terrains	Yes	Medium High / 0.06 s to 0.26 s	Santos *et al.* [35] (2019)
Multi-point measurement in potato ridge cultivation	ACO	Off-line	Static	N/A	2D	Parallel rows of potatoes	Shortest distance	N/A	No direct application to any real robot	No	Complex / N/A	Mai *et al.* [38] (2019)
Navigation of semi-autonomous agricultural vehicles with trailer	Model proposed by the authors	On-line	N/A	Yes	2D	N/A	N/A	Tractor with trailer: -limited steer angle; -limited steer rating;	Swath distance from pickup centre reaches 1 meter error	Yes	N/A	Pichler *et al.* [44] (2020)

TABLE II: Coverage path planning applications in agriculture

Agricultural application	**Path Planning Approach**	**On-line or Off-line**	**Dynamic or Static environment**	**Optimal Path**	**Geometry Features**			**Optmisitation Criteria**	**Robot Restrictions**	**Limitations**	**Tested in real scenario**	**Computational Complexity / Processing time**	**Ref.**
					2D/3D	Terrain Configuration	In field Obstacles						
Coverage field farm with agricultural machines	Hamiltonian Graph exploration based approach	Off-line	Static	Near- -optimal	2D	Irregular shaped polygons (convex and nonconvex)	Both cases considered	Minimise overlapping and number of manoeuvres	Farm Tractor: -limited steer angle; -limited steer rate;	N/A	No	NP-complete / N/A	Taïx *et al.* [45] (2006)
Coverage fields with autonomous or human-driven agricultural machine	Greedy algorithms for division of area into sub-areas and Heuristic algorithm for selection driving direction	Off-line	Static	No	2D	Complex shaped fields (curved lines)	Yes	-Consider fuel refill paths; -Cost function weighted with: the relative efficiency (operated area divided by total time); the normalised area (area of a generated sub-area divided into the remaining area) and the normalised distance (travelled distance in a sub-area excluding the travelled distance in the headland area)	N/A	It is possible to find cases in wich this method doe not offer a solution	No	NP-hard / 4 minutes	Oksanen *et al.* [25] (2009)
Intelligent coverage for agricultural robots and autonomous machines	2D/3D GA-based approach	Off-line	Static	Yes	Both	Complex and irregular shaped fields (curved and not plain)	Yes	Optimal driving direction which minimizes energy consumption (fuel);	N/A	Can result in coverage plans that require increased operational time	No	Complex / N/A	Hameed *et al.* [46] (2014)
Rural Postman Coverage in steep slope vineyard	A* and Dijkstra search in graphs	Off-line	Static	Yes	3D	Irregular curved vine rows in terraces with high slopes at the edges	Yes	Find optimal permutation of tracks to ensure coverage;	Tested with Farm tractor, where U-turn manoeuvres not possible;	The amount of wicker may require a repetition of a specific path, which goes against the principles of most CPP problems	Yes	NP-hard / N/A	Contente *et al.* [50] (2016)
Side-to-side coverage for agricultural robots	Grid-based 2D coverage projection on 3D terrain with cylindrical approach for optimization to the topography	Off-line	Static	N/A	3D	Accepts all topographical types os terrain	No	Minimise skip/overlap areas between swaths	N/A	Cylindrical approach cannot differentiate between skips and overlaps	Yes	N/A	Hameed *et al.* [47] (2016)
Coverage for a fleet in an agricultural environment	Mix-opt (developed by authors) - a mix of various permutation operators	Off-line	Static	N/A	2D	Parallel Rows	Yes	Given a set of n tracks and m vehicles, determine a set of routes such that each track is covered exactly once by any of the involved vehicles while minimising the total cost of covering all the tracks	Farm Tractor: -limited steer angle; -limited steer rate;	-It is presented just a route planning tool; -Authors defend the implementation with a faster language;	No	N/A	Conesa *et al.* [53] (2016)
UGV to measure ground properties of greenhouses	Back and forth strategy	Off-line	Static	N/A	2D	Parallel rows of vegetation in greenhouse	Yes	The path must pass through all the points, with the shortest possible longitude and without changing over time.	Differential Robot	N/A	Yes	N/A	Ruiz *et al.* [54] (2017)
Agricultural robot swarm for seeding task	Developed by authors (algorithm not specified)	On-line	Dynamic	N/A	2D	Irregular polygons on plain agricultural areas	Yes	- Find a path to cover the entire seeding area; - Find uniform workload distribution between robots; - Find optimised overall path length considering limited on-board supply of energy and seeds;	Limited supply of energy and seeds;	- System tested with a small number of robots; -Moving from big machines to swarm robots may not be well accepted in the first demonstrations;	Yes	N/A	Blender *et al.* [48] (2017)
Precision pollination in greenhouse	Voronoi Graphs with Dijkstrasearch and Dynamic windows approach for local obstacles	On-line	Dynamic	No	2D	Parallel rows of plants in greenhouse	Yes	Cover all polinization points minimising distance driven by robot	Differential Robot with arm manipulator	The problem has to be reformulated to generate paths which ensure flowers near the end of their polinization are reached sooner	Yes	Medium-Low / N/A	Ohi *et al.* [52] (2018)
Coverage Path Planning for ground robot with aerial imagery	A* algorithm search in graphs with gradient Descent optimization for smoothing the trajectory	Off-line	Static	Yes	2D	Hilly Vineyards with parallel vine rows	Yes	Cover all of vineyards rows while minimising distance	N/A	- Path labels in UAV imagery contain non-continuous rows; - Weakness when environments deviate significantly from one parcel to another	Yes	Medium / N/A	Zoto *et al.* [51] (2019)
Optimize harvesting area of a robot combine harvester of wheat or paddy	N-polygon algorithm to determine optimum harvesting area (Developed by authors)	Off-line	Static	Yes	2D	Convex and concave polygon fields	No	Cover area without overlaps or skips in the shortest time	Big dimension agricultural tracks machine	N/A	No	N/A / 5 minutes	Rahman *et al.* [49] (2019)

complexity class used to classify decision problems [55].

The analysis of the review leads to the conclusion that although path planning is widely explored for industry and indoor environment, its applications in ground robots to agricultural environments are scarce. Coverage path planning is slightly more advanced as it is a recurrent problem in farming. However, for precision agriculture tasks, Point-to-Point planners are useful, as the goal may be to perform an autonomous task to a specific number of plants. For example, for pruning tasks, the robot must only visit the selected plants and not the entire field. To conclude, path planning research in agriculture is in the right "path" to achieve the automatisation of agricultural areas. Now, the focus of the research should proceed in the validation and optimisation of the proposed methods through intensive tests in real agrarian environments.

V. CONCLUSION

The current paper presented a review of path planning for ground robots in agricultural domains. It examined the agricultural application and described the constraints imposed either by the robot configuration or the type of the terrain. This work list technical details such as the path planning algorithm, the type of environment, the geometry features of the terrain, the optimisation criteria, the limitation of the method, the computational complexity, and the realisation of tests in real scenario. The analysis divided path planning methods into two sub-categories: Point-to-Point and Coverage Path Planning. The findings indicate that the coverage field approaches are lightly advanced than Point-to-Point path planning in agriculture, which happens because coverage tasks are a frequent requirement for agricultural purposes, yet, for precision agriculture, it is necessary to have Point-to-Point navigation. The review did not indicate any preferred approach as the authors resorted to various path planning methods. Less than half of the authors claimed to have performed real scenario tests. So, for a proper integration in the automatisation of agricultural tasks, the research should focus on the optimisation and validation through intensive tests in real agricultural scenarios, and make more agricultural land sensors data-sets available to the research community.

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