IJCSE International Journal of Computer Sciences and Engineering Open Access
Survey Paper Vol.-7, Issue-3, March 2019 E-ISSN: 2347-2693

A Survey on Coverage Path Planning Algorithms for Autonomous Robots in Agriculture

Kalaivanan Sandamurthy[1*] , **Kalpana Ramanujam**[2]

[1,2]Dept. of Computer Science and Engineering, Pondicherry Engineering College, Puducherry, India

[*] *Corresponding Author: kalai_4390@yahoo.co.in*

DOI: https://doi.org/10.26438/ijcse/v7i3.815827 | Available online at: www.ijcseonline.org

Accepted: 13/Mar/2019, Published: 31/Mar/2019

Abstract**—** Path planning has been a challenging task for researchers working towards automation in various fields. The objective of coverage path planning (CPP) is finding a path that covers all the points in the search space, avoiding obstacles. Coverage path planning is a key component in many robotic applications such as and not limited to automated machinery in agriculture, autonomous underwater vehicles, unmanned aerial vehicles, lawn mowers, floor cleaners, and industrial robots. Major research has been done on optimizing the solution for covering path planning algorithms. However, there is no major survey available on the application of coverage path planning in agriculture. This paper aims to fulfill the void by discussing a detailed survey on the techniques, methodology and the performance of covering path planning algorithms applied in the field of agriculture. Finally, various techniques are compared based on the parameters used for validating the performance of the algorithms. This work is aimed to be a starting point for researchers who are initiating their endeavors in coverage path planning to be applied in the field of agriculture. This work is steered in that direction, to provide a comprehensive review of the various CPP algorithms proposed so far, for application in agriculture.

Keywords**—** Coverage Path Planning, 3-Dimensional Coverage, Agriculture, Autonomous Systems

---

I. INTRODUCTION

Path planning is the task of finding a feasible path from starting position to the target position avoiding obstacles in the environment [1]. The environment can be classified as either static or dynamic. Frequent re-planning and updates are required for path planning in the dynamic environment. Research in path planning first began in the 1960's aimed to design autonomous robots, but developed momentum after the ground breaking research publication of Lozano-Perez in 1979[2]. The well-known path planning problem known as the piano mover's problem to find a collision free path from start to target node is PSPACE-hard, implying NP-hard[3,4].
The objective of coverage path planning (CPP) algorithm is to find a path that visits all the nodes in a given environment avoiding obstacles. This algorithm is applied in many areas such as lawn mowers[5,6],painting robots[7], agricultural robots[8,9],cleaning robots[10],mining robots[11] and underwater vehicles[12]. A set of criteria [13] has been defined for autonomous robots to perform coverage path planning which is considered as the back bone for most of the research in the area of coverage path planning. They are as follows:

1. Robot must cover the entire search space.
2. Robot must fill the region without overlapping paths
3. Continuous and sequential operation without any repetition of paths is required.
4. Robot must avoid all obstacles.
5. Simple motion trajectories (e.g., straight lines or circles) should be used (for simplicity in control).
6. An ''optimal'' path is desired under available conditions.

It is also noted that it is not possible to satisfy all the above mentioned criteria for complex environments. Hence prioritization of constraints is followed, especially for implementation in the field of agriculture. In literature, Coverage path planning problem is related to covering salesman problem which is a variant of travelling salesman problem. In travelling salesman the goal is to visit each city whereas in covering salesman problem a neighbour of each city has to be visited. Travelling salesman problem is known to be NP-hard.

Coverage algorithms are classified as either complete or heuristic depending on the degree of coverage provided for the environment. Heuristics rely on a basic set of behaviours to complete the task at hand. A sweeping robot [14] employs a heuristic known as repulsion, in a multi robot environment ensuring they spread as wide as possible thereby covering the environment uniformly in a less amount of time. Instead of planning paths they select directions at random. Randomizing the search doesn't provide complete coverage but has its advantages. The cost of the search is greatly reduced both in terms of hardware used (sensors) and computational complexity for finding a solution. The theory behind this is that if a floor is sweeped long enough then it is clean. Some floor cleaning robots like trilobite developed by Electrolux and Roomba by iRobot [15] rely on this strategy. The main advantage of this technique is that the need for complex sensors is eliminated. Therefore randomization can be used to build robots involving less cost to solve coverage problems. Extensive research has been done [16,17] which conclude that robots employing randomized strategies can be built at one fifth of the cost required to build robots which use complete search strategies.

Another method of classification proposed by Choset [18] is offline and online algorithms. Offline algorithms have a priori knowledge about the environment. This makes the computation of paths to be performed before the robot is introduced into the field, thereby classifying it as a master slave system, the master being the processing unit, and the bot being the slave. This bot can't be classified as an autonomous robot. This system also introduces the possibility of many slave robots operating in the field controlled by a master. It may be useful in industrial applications where the environment is stable, but not suitable in an agricultural field since the topology of the field is subjected to constant change and also having a priori knowledge of the field is not possible always.

Online algorithms do not have prior knowledge about the environment to be handled. Hence they have real-time sensors to analyse the target environment. They are also called as sensor-based coverage algorithms. They can never yield an optimal solution for all environments.

A survey on coverage path planning was first presented by Choset [18] in 2001. An updated survey was published by E.Galceran [19] in 2013 where the achievements and field application of coverage algorithms are discussed. This paper surveys the various methods proposed to solve coverage path planning in agriculture. This paper is aimed to support researchers who are interested to solve coverage problems for application in the field of agriculture.

The rest of the article is organized as follows. Section 2 reviews the various decomposition techniques used in coverage path planning and some examples using the techniques validated in simulation or using real time robots. Section 3 discusses about the algorithms proposed to perform coverage in agricultural fields. They consider a 2-dimesional model of the field to perform coverage. The use of multiple robots to perform coverage in agriculture is outlined in section 4. Section 5 reviews methods which have modelled the agricultural field in 3-dimension for coverage. The authors conclude in Section 6 detailing the scope and future directions of the survey.

II. DECOMPOSITION TECHNIQUES

In literature, the first step in solving coverage problems is to decompose the target environment into sub regions to perform coverage. They are classified as approximate, semi-approximate and exact cellular decompositions techniques [19, 20].

A. Approximate cellular decompositions

Also known as grid representation, here the environment is decomposed into grid cells of equal dimensions. This method of decomposition was first proposed by Elfes and Moravec[20,21]in 1985 using sonar based mapping for mobile robots. Each grid is assigned a value to identify the presence of obstacles. The assigned value can be either binary or a probability value. The basic structure of a grid cell is square, but use of other shapes has also been proposed. The use of triangular grid cells was proposed by Oh et al. [22]. It is claimed that it offers higher resolution when compared to a rectangular structure.

Zelinsky et al., [23] proposed a grid based method for coverage problem in unstructured environments using distance transform as a measure. A distance wavefront is propagated through all the cells starting from the goal position. The initial position of the robot in the environment is the starting point. A value 0 is assigned to the goal cell and value 1 to the cells surrounding it thereafter increasing numerically to all the surrounding cells until the start cell is numbered. Instead of following the path of steepest descent the robot follows the path of steepest ascent for coverage. A movement to a grid cell closer to the goal happens only when all the neighbouring cells away from the goal have been visited. The use of numeric potential function [24,25] and path transform to find a path have been implemented and compared. The use of potential fields has high computational complexity and also clearance information is not considered whereas path transform does not have these drawbacks. Clearly the path transform produces an optimal path comparatively. The advantage of using distant transform over other path planning approaches is that they can modified for different types of navigation modes such as conservative, adventurous or optimum coverage planning[26]. The algorithm was implemented in Yamabico robot. One advantage of this algorithm is that the start and goal node can be specified. It can be classified under the class of offline algorithms.

Online coverage using a generalized approach of the wave front algorithm has been proposed by Shivasankar et al., [27].

1. Spanning tree based coverage

An online algorithm using spanning tree approach [28] covers every grid only once, which cannot be applied in agricultural environment since frequent revisits are needed.

The algorithm is implemented recursively, and after execution the robot moves to its starting position.

A backtracking spiral algorithm [29] intends to cover partially occupied cells using wall following, as opposed to spanning tree approach where only unoccupied cells are covered. This can be classified as an online algorithm. Both of them are validated only in simulation.

A hybrid coverage algorithm [30] combining these two methods is validated using real time robots.

2. Coverage using neural network

Lee et al. [31] proposed the use of neural networks to solve coverage problems. The 2-dimensional grid environment is organized as a neural network. The membrane model for biological neural system [32] is used to derive a shunting equation for determining the dynamics of each neuron. It can be classified as online algorithm since the robot can operate in dynamic environments. The algorithm is designed for floor cleaning robots. Further modifications to this approach Use a triangular representation of the grid[33]a bio inspired neural network[34] for solving coverage problems is proposed by adding a local path planning model which is claimed to reduce complexity in computation.

The use of hexagonal grid structures is proposed by Paull et al., [35, 36]. It is specifically designed for mine operations with the use of side looking sensors. There are two advantages in the usage of hexagonal grids. The distance between two adjacent cells are the same and with the usage of side looking sensors more cells are covered at a given instance. The drawback is that presence of obstacles is not considered. The algorithm is evaluated both in simulation and real time robot operation. Nonetheless without the consideration of obstacles this will not be suitable for usage in agricultural operations.

B. Exact cellular decomposition

In exact cellular decomposition the free space is divided in cells which do not overlap and whose union is the search space. Simple back and forth regions can be used to traverse these individual cells thereby performing a coverage operation. A typical use of this zigzag pattern is employed to solve the lawn mowing problem. An adjacency graph can be used to represent this type of decomposition, wherein a cell is considered as a node and the boundary between two cells are considered to be an edge. The planning of path can be described in two simple steps. First the free space is broken into cells and stored as an adjacency graph. Then a path is planned in the adjacency graph by visiting each node exactly once. Trapezoidal decomposition and Boustrophedon decomposition are two classical decomposition techniques which use this methodology.

In trapezoidal decomposition [37, 38] the environment is decomposed into trapezoids and simple back and forth motions is used to achieve coverage [39] using the adjacency graph. This method comes under the class of offline algorithms. An online version using trapezoidal decomposition for planar environments with obstacles is also evaluated in [40].

C. Boustrophedon decomposition

Originally proposed by Choset et al.[41,42] this method overcomes the limitations of trapezoidal decomposition wherein multiple cells which are generated in trapezoidal decomposition can be combined to form a single large cell so as to decrease the computation time for coverage. This is due to the fact that only convex cells are created in trapezoidal decomposition. This method can be classified as an offline algorithm since a priori information about the environment is required.

A more generalized form of boustrophedon decomposition was proposed in [43] based on the usage of Morse functions [44]. One drawback of this method is that rectilinear environments cannot be used. An online algorithm for coverage using Morse based decomposition [45] uses Reeb graph [46] to store and construct the decomposed environment.

A coverage algorithm based on the detection of natural landmarks was proposed by Wong et al.,[47]. It can be classified as an online algorithm proposed to perform coverage in simple planar environments. Simple landmarks are used to perform decomposition which is also known as slice decomposition. This algorithm can handle elliptical, polygonal and rectilinear environments with obstacles. Five different events such as split, merge, lengthen, shorten and end is used to determine cell boundaries.

Contact sensor based coverage was proposed by butler et al., [48] for rectilinear environments. It can be classified as an online algorithm designed for an automated assembly system.

Coverage algorithms based on the representation of search space as graphs have been proposed by Xu [49]. This can be applied for street networks. It is an online algorithm which can be applied to vehicular networks.

D. Semi approximate decomposition

Semi approximate decomposition follows the strategy of partial discretization, wherein the search space is divided into cells of same width, but top and bottom of the cell can be of any size [12,50]. The robot can start at any point and zigzag pattern is followed along grid lines to achieve coverage. This is a recursive procedure wherein free space which is not covered known as inlets are identified and the algorithm is applied recursively. Depth first order is followed in covering inlets. Each inlet is covered only once as the robots remember the entry point. A special form of inlets known as diversion inlets where the space is not visited or visited more than once employs special procedures by moving the robot along the boundary. When islands are present in the search space minor modifications are made ensuring that all islands are covered. This idea is used [51] for robots operating in the bottom of sea. This was validated in simulation.

An online decomposition method for 3 dimensional (3D) planes was proposed by Atkar et al., [52] by extending the idea of Morse decomposition. Their primary area of application was spray-painting robots hence the presence of obstacles is not considered here. This work was extended to an offline mode where a Computer-aided design (CAD) model is used as input. This was validated in simulation and also by using real time robots. An offline approach for Unmanned Aerial Vehicle (UAV)to perform 3D urban coverage[53] was evaluated by simplifying the buildings into hemispheres and cylinders.

III. COVERAGE IN AGRICULTURE

With the advent of automation technologies every industry is being tested and automated with latest technology, and agriculture being no exception. Automation has been applied to field operations such as seeding, harvesting, spraying, fertilizing, and ploughing to maximize efficiency and to optimize the use of resources. Field robots are designed to be fully autonomous with minimum or no human intervention. Some of the robots developed for agriculture in the past decade are cherry harvesting robot [54], apple harvesting robot[55], cucumber picking[56], kiwifruit picker[57], melon harvester[58], strawberry picker[59], and orange picker[60]. Path planning is an inevitable component in any autonomous robot. When it comes to agriculture, complete coverage of the field is a prerequisite for any operation involving an autonomous robot. Various algorithms have been proposed to solve coverage path planning in agriculture. They are classified in terms of the decomposition technique used, complexity, efficiency, advantages and drawbacks.

A. Coverage of fields modelled in 2-dimension. Landmark based coverage using Genetic algorithm

Hameed et al., [61] proposed a coverage approach for navigation of agricultural robots. They start with assumption that boundaries and obstacles are fixed throughout the year so that path planning could be done in advance. It is claimed that their algorithm can be applied to complex field structures involving obstacles without any kind of human intervention.

1. Geometric representation

Representation of the field is done in three stages. Track generation is performed in the first phase wherein the boundaries of the field and also the obstacle's boundary are analysed. Field tracks parallel to a driving angle is used to fill the field polygon. The driving angle is user defined and the width between lines is also user defined. The intersection of the field and obstacle boundaries with track line is obtained and tracks within the field are taken, eliminating the remaining parts.

Second stage: A track generated intersects at two points with the field boundary. If an obstacle is present in between then the track is divided into two different line segments with the end points touching the obstacle boundary and the field boundary at each end respectively. After generation, individual tracks are clustered into blocks. The driving angle and direction determine the number of blocks generated.

The third stage is headland polygon generation. The robot must pass through all blocks only once avoiding obstacles to perform coverage. This is an optimization problem with the objective function is minimizing the distance between blocks and the decision variable being order of blocks. A function of the entrance points from the configuration of field tracks is used as exit point in a block.

2. Real valued Genetic algorithm

Genetic algorithm is used to solve the coverage problem. Real valued encoding is used for entrance points which the authors claim to speed up convergence and decrease computation complexity. Permutation encoding is used for representing decision variables as a sequence of blocks. The input is two sequenced integer set, wherein the sets representing the block entrance point and time ordered block representation. The output is the Euclidean distance of blocks in 2 dimensional spaces. Mutation and crossover operations define the output of the genetic algorithm [62]. Inverse mutation is used to avoid a non-viable block order. The generation of the final path is not only dependent on the coverage of tracks within blocks but also paths for headland operations are needed to perform complete coverage of the field. This time varies for various operations such as seeding where headland paths are executed after coverage of main blocks but in harvesting it must be done before computation of main blocks. Considering these situations the author has developed two algorithms, one for input material flow and other for output material flow operations.

The performance of the algorithm was validated in two cases. One for small scale problems wherein the number of blocks is less than or equal to 4.That is 4! =24 solutions with repetitions. Here all possible sequences can be analysed and a solution with minimum distance is chosen thereby guaranteeing global optimum.
The algorithm is validated by considering two fields of different sizes. Table 1details the parameters that are considered for validating the proposed algorithm. Table 2 details the genetic algorithm parameters that were used to obtain a feasible solution. The agricultural field used for validation is located Germany.

Table 2 Genetic algorithm parameters

GA parameters	Population size	Number of generation	Crossover probability	Mutation probability
Case 1	100	50	0.8	0.9
Case 2	100	100	0.8	0.01

Table 1 field parameters

Field parameters	Field area (Hectares)	Number of obstacles	Driving angle (degrees)	Width (meters)	Number of headland passes	Computation time [block generation] (seconds)	Time taken to obtain a feasible solution (minutes)
Case 1 Small scale	5.54	1	4.5	9	2	0.18	0.47
Case 2 Large scale	94.03	2	84	18	2	0.28	14.41

The authors have made an assumption that the field topology does not change over in a year which is unlikely. Since the proposed method is an offline algorithm the application in real time fields may not guarantee optimal coverage. A notable point here is that vehicle parameters have been taken into account while validating the efficiency of the algorithm which makes it a strong candidate to be tried for real time implementation.

B. Sub-region based coverage using Depth first search

G.Zuo et al., [62] proposed a solution for coverage in agriculture based on the concept of sub-regions. The authors claim that methodologies such as cellular decomposition [63], neural network [64], back–turn method[65] and genetic algorithms[61] proposed for solving coverage path planning have the drawback of producing many turns in a narrow area. They claim that their algorithm minimizes the number of turns in an agricultural field. The robot is assumed to have a priori knowledge of the environment; hence it can be classified as an offline method. The total time taken by the robot to perform coverage is denoted as the sum of time taken to perform straight line motion and time taken to perform turns in the field. It is claimed that if the number of turns is reduced, then the time taken to perform coverage is minimum since the total time taken for coverage is directly dependent of the number of turns performed.

The algorithm proceeds in three steps. First the longer side of the environment is taken and then the search space is divided into sub regions without preserves. In the next step the sub regions are modelled as nodes of an undirected graph. Traversing the graph ensures complete coverage. Adjacency graph is used to save space and for ease of computation ensuring that each vertex is visited only once during the traversal. Depth first search is employed to achieve coverage. The concept of stack is used in execution of the algorithm. Initially every sub-region is marked as uncovered and after covering it is pushed onto a stack. The algorithm is validated in simulation and compared with back-turn method and inner spiral method. For the same environment back-turn method took 121 turns, repetition rate was 7.59% and total path length of 461. Inner-spiral method took 99 turns, repetition rate was 11.67% and path length was 557. While the proposed sub-regional coverage took only 81 turns, repetition rate was 5.02% and path length 448.5. It is evident that the sub-region method outperforms the other two methodologies. The algorithm is validated only in simulation and also only rectangular fields are considered whereas real time farms are of different shapes and size. So real time application of this algorithm does not guarantee complete coverage.

C. Grid based coverage using Genetic algorithm

Ryerson et al., [66] used genetic algorithms to achieve coverage for vehicles used in agricultural farms. The search space is modelled as a polygonal structure defined by the field boundaries. At least three points of the vertices are needed to obtain coverage. Two types of representation are followed for modelling obstacles. Obstacles are classified either as a circle with centre point and radius to define its location and size or as a polygon wherein it is represented using a list of vertices [67]. The search space is decomposed in the form of grids to achieve coverage. The grid cells without obstacles are given a unique identification number starting from the origin position. The vehicle has an on-board controller to sense a path. Width of the vehicle is defined as a parameter. The logic behind this is grids are formed on par with the width of the vehicle such that if a vehicle passes over a grid it is assumed to be fully covered. Path is represented as a list of points in 2-dimension. These are associated with a fitness value thereby serving as the population in genetic algorithm. The ideal path is defined as the one which achieves total coverage of the search space without any repetition in path, avoiding obstacles and being the shortest path possible. These were the four parameters used to achieve an optimal solution. They are assigned different weightages to define the quality of the solution.

As with every genetic algorithm, the basic functions such as selection, reproduction, mutation and crossover are used. Roulette-wheel selection is used which ensures that candidates with highest fitness have higher probability of being selected. Basic crossover function wherein the parents are cut at a random points and information is exchanged from both the parents to the offspring. The creation of new path is defined as reproduction. Mutation is implemented by a three action mutation algorithm comprising of delete, insert and modify actions at a given point. The choice of implementing one of the three actions is random. Insert action is performed by adding a new point to the path thereby increasing the path length, delete by deleting point in the path and modify by replacing an existing point by adding a point that is not present in the existing path sequence. In addition to these some special functions have been added which are detailed below.

Reordering the points without changing the total number of points in the path sequence is done by swap function [67]. Reordering the points by changing the entire order of points in the path sequence is done by reorder function. Another important function is the remove crossing function which removes path that crosses over other paths thereby ensuring that there is no repetition in the final path. These special functions play a vital role in tuning the proposed genetic algorithm to perform optimal coverage.

The paths generated by GA has many sharp turns and edges, which is practically not possible to be performed by a tractor. Vehicle parameters such as size, speed and turning radius must have been considered when developing an algorithm for autonomous vehicles. The mutation function in the algorithm added more points in the final solution for coverage. Genetic algorithm in itself is a random process which gives different solutions for consecutive runs. The final path was optimal in the sense that it avoided obstacles efficiently.

The authors claim that the performance of the algorithm can be increased by increasing the number of generations which can give a better solution and also by giving a set of predefined paths in the initial solution which gives the algorithm a ‘jump start’ to give a better solution. However this was not tested in the proposed algorithm.

D. Coverage by graph abstraction

Sorensen et al., [68] proposed a coverage solution for autonomous agricultural robots as a replacement for traditional machines. Graph abstraction followed by the principle of network routing is used to implement the solution. The basic processes involved in agricultural management is identified and broken into sub-tasks namely routing, scheduling and sequencing for designing an autonomous machine. headland generation and headland routes are the key components.. The next step is to cover the field without overlapping and repetition of paths. The sequence of execution of the generated optimal path defines the efficiency of the algorithm. Prior information of the field is obtained to perform coverage thus classifying it as an offline approach. A graphical approach [69] is used to decompose the search space. The graph generated is the basis for formulation of a coverage solution. First the field is divided into sub fields, which is considered as a closed polygon with the boundary representing the edges and the vertices representing the corners in the field. This information is stored as a graph. On the basis of cost associated in traversing an edge a weight is assigned to every edge. Additional edges and vertices are added to compensate the vehicular dimensions and headlands. All edges in the graph are to be visited to achieve coverage. This problem is related to the Chinese Postman problem. i.e. finding a closed walk in the graph by visiting all edges at least once with minimum cost. Addition of extra vertices and joining them with edges for headland operations introduce many unwanted turns in the resulting solution. Hence the process of headland and access path generation has been separated from the main field coverage problem.

The headlands are eliminated in the graph before generating coverage for the field. Number of turns is minimized by choosing the longest edge for parallel paths. After identification of headlands the graph is reduced into single vertices by joining headland vertices and graph. The resulting graph is similar to Rural Postman problem which is solved by finding a closed walk such that edge costs are minimum. It is a NP-hard combinatorial problem. A heuristic approach assuming simple turn at headlands reduces the complexity in planning.

The field is divided into sub-fields and is represented as a weighted connected graph. A closed walk in the graph is computed by visiting each node only once with minimum weight associated in the path. Headlands and headland connections are identified and a new graph is generated. Then the vehicle location is initialized and the next headland vertex that has not been visited is identified. a region filling path is generated with the help of heuristic planner.

Sub fields and boundaries are identified with the help of aerial map. The result is used to generate a graph where the edges are assigned cost based on the distance function and coverage is obtained for the graph. Then headlands are collapsed into single vertices for region filling operation. The result is shown to perform a complete coverage of the given field.

Due to the low computational requirements of this algorithm, it is more practical for use in obtaining an optimal solution for autonomous units in the fields. This is tested only in simulation and also vehicle parameters such as speed, size and driving angle are not taken into account.

E. Coverage using Boustrophedon decomposition and Ant-colony algorithm

Zhou et al., [69] proposed coverage for irregular agricultural fields involving multiple obstacles. They propose it for non-capacitated operations i.e. single route cannot be determined to perform complete coverage of the field. The parameters considered for input are the boundary of the field and obstacles ordered as a set of vertices. The headland passes for field and obstacles driving direction, width and turning radius of the vehicle and a threshold parameter which classifies the obstacle into various types as A, B, C and D.

In the first stage the field headland area is determined and obstacles are categorized into four types. Obstacles which are very small in size are classified as type A. they do not affect the generation of coverage plan. Obstacles which are close to the boundary of the field area are classified as type B. They are considered as part of the boundary and headland is generated around the obstacle. Two obstacles which are close to one another where the distance between them less than the operating width is classified as type C. They are considered as a single obstacle during path generation. The remaining obstacles fall into type D classification including the ones in type C after integration. Parallel tracks are generated to cover the field body. Rotating callipers method [70] is used to generate minimum–perimeter bounding rectangle (MBR).

Decomposition of field into blocks is performed in the second stage. Boustrophedon decomposition [42] is used to perform decomposition and an adjacency graph is constructed. If two connected blocks have a common edge, they are merged together. Then the tracks generated earlier are clustered into the blocks according to their position.

In the third stage traversal of the graph is performed by considering the graph as an undirected weighted graph with nodes and edges. In order to avoid travelling in the field area connection between blocks is performed only when nodes in both the blocks are located in the inner boundary of the field or outer boundary of an obstacle.

Ant colony Optimization [71] was used to solve the optimization problem. The number of ants is equal to the number of nodes in the graph. As the number of generation is increased the convergence towards optimal solution increased. The complexity is directly dependent on the number of obstacles present in the search space.

This method not only evaluates the performance in simulation but also compares it with real time results of the field which is a novel approach. Multiple obstacles up to5, were tested with this algorithm which is also a unique feature. Due to very less computation time, the authors claim it can be used as an online system.

F. Coverage using trapezoidal decomposition

Timo Osaken and Arto Visala [72] proposed two different algorithms to achieve coverage in agricultural fields. Fields in Finland were considered for testing their algorithms.

The algorithm proceeds by splitting the field area into trapezoids. The objective is not to find an optimal solution; rather it is to find a feasible solution. The algorithm is implemented using greedy strategy. The blocks are decomposed into trapezoids and then merged in a greedy way, by identifying the block with best cost function. This method is continued until the whole field area is split into trapezoids. Trapezoidal decomposition is preferred as it produced straight, parallel tracks which were suitable for driving. Trapezoids which are parallel and having a pre-defined angle (determined by a threshold value) are merged together. An optimal control technique was developed to find the minimum turning time. Determining the angle of driving is determined by using a simple heuristic [split and merge] algorithm. Areas with drive restrictions are identified by considering the block as an obstacle which is done in the split phase.

Fields in the region of Uusimaa, Finland were considered validating the algorithm. The vehicle parameters were width 2.5 m, headland 7.5 m, driving speed of 10km/h in straight lines and 6 km/h in turnings. The solutions were verified manually for feasibility. The algorithm gives an optimal solution provided no obstacles are present. Fields with varying geometry were used to test the algorithm. A special case of executing this algorithm in under -drained fields was done. The decomposition happened forbidding the direction of driving along the path of the pipe lines. There was only 0.2% change in efficiency when compared to executing the algorithm without consideration of underground pipe lines.

The algorithm used a top-down approach to decompose the field area. The algorithm considers fields having straight line boundaries which is always true in case of agricultural farms. It doesn’t guarantee an optimal solution for coverage.

1. An online approach for coverage using predictive recursion technique

The drawbacks in the first algorithm were considered in the design of this algorithm. Model predictive control is used to limit the search space of swaths. Polygonal fields were considered for testing this algorithm. In the previous algorithm, driving only in straight lines was assumed to achieve coverage. In this method, the swaths are assumed to be present side by side with other swaths or with the field boundary and the width are constant. Driving pattern is considered as either driving around the polygon or driving some swaths in one direction and then reversing the direction of driving to come back. Searching is to be done in both clockwise and anti-clockwise direction. If a swath is skipped in clockwise direction, then it must be skipped in the reverse direction too. Polygon offsetting is used to identify the search space by walking the field boundary. Straight skeleton method [73] was used to solve this computational problem.

The routes were generated based on polygon offsetting algorithm. In situations where the field has many vertices, the line segments are merged to polylines. The costs associated with all possible routes are compared taking into account the turning time, and the best route is selected. Whether the turning area is located inside or outside the field is not taken into account, as a strategy to reduce computation time

An algorithm for automatic refilling operations such sprayers, harvesters, spreaders is proposed. For simulation of this algorithm parameters such as application rate, tank capacity and safety margin is taken into account. If the tank is full then a route is generated to the nearest service point and executed.

The algorithm is designed to handle non-convex fields by implementing simple heuristics. The first algorithm uses a top-down approach wherein the second algorithm is based on a bottom-up approach. After the first stage of decomposing the search field simple heuristics is used which does not perform well when the field area is scaled up.

G. Coverage by graph traversal using trapezoidal decomposition

Bochtis et al., [74] proposed a methodology by integrating the two algorithms presented in 3.6[72] to provide complete coverage in agricultural fields.

The first step is to split the field into blocks. Trapezoidal decomposition is used to achieve this and blocks are merged wherever possible. Headlands are laid automatically only at the end of a block. Regions with prohibited driving such as under drainage, obstacles are considered. Coverage is achieved by modelling the field blocks as a weighted undirected graph and traversal is done by visiting each node exactly once with minimum cost.

The operation of the algorithm can be classified into two stages namely, A randomization phase, where best pattern is chosen and an improvement phase wherein local search techniques are used to perform heuristics. Fields with multiple obstacles are not evaluated thereby questioning the algorithm's application in real time scenarios.

IV. MULTI ROBOT COVERAGE

This section deals with the various multi-robot techniques proposed for coverage in agricultural fields. Multi robots can be either autonomous or master slave systems based on the area of application. Multi-robot coverage has been implemented in industrial robots with success since the search space is well defined and no adhoc obstacles are to be considered which inturn greatly reduces the complexity of the problem. Multi-robots using boustrophedon decomposition [75], spanning tree coverage method[76], neural networks[77], graph based[78] and bio inspired methods[79] for achieving coverage in other areas have been proposed and tested for efficiency.

A. Multi-robot coverage for sub-regions using depth first search

Peng Zhang and JunfeiQiao [80] proposed coverage planning and tracking for agriculture, based on master slave robot system. The master performs coverage of the field while the slave assists the master for fuelling and transportation purposes. Decisions are made by the master while the slave follows the instructions from master robot. Back-turn method was used by the master to achieve complete coverage.

The search space was divided into sub-regions without preserves. The problem is modelled as an adjacency graph and Depth-First search is used. Sub-regions are covered in the order of DFS. The longer side of the region is covered first to minimize the number of turns. Depth-First search is performed by implementation of a stack model.

The slave follows the master by means of a TRACK algorithm. Initial communication is broadcasted by the master instructing the slave to track the master bot at a defined offset and relative angle. Distance and angle parameters are included in the TRACK algorithm. The regions of the slave are identified as unacceptable, tune and ideal region. If the slave is present in an unacceptable region then is uses maximal rate and angle to move to the destination instructed by the master bot. If present in tune region, it tunes to the rate and angle with respect to the distance to destination. In ideal region, the current rate and angle settings are to be followed. Only a single slave bot is considered in the simulation. Also the use of back-turn method has been proven to be inefficient as it generates more number of turns when compared to other methods such as inner spiral and sub region coverage [62].

B. Multi-robot coverage using Grid decomposition

Bochtis et al., [81] proposed a path planning approach for navigation of sub-units in agricultural fields. In a multi-robot system the overall efficiency is the sum of individual system's performance. As significant amount of research has been done in the planning of primary units, the authors focus on path planning of sub unit bots. A decoupled approach between the primary and sub units is followed here wherein the path of the primary unit is known and sub units act accordingly. Both convex and non-convex fields are considered for implementation.

In the first stage, the field is decomposed into grid cells with co-ordinates. Each cell falls under either free, obstacle, initial or goal cell. One or more goal states can be present in a field. Two modes of service, stationary and On-the-go services are considered for the sub units. For stationary service the ends of each track line is a goal node, i.e. two goal cells for every track in the search space. Path planning proceeds by modeling the action space as a directed transition graph. Shortest path with least number of steps is solved using modified version of breadth first search algorithm.

In the second stage, paths of same length are compared by their corresponding Euclidean distance and the shortest one is chosen. Parameters such as path of primary unit, geometric representation of field and initial state of service unit are taken as input. Agricultural field in Denmark, was used as test field. Scenarios were simulated and both stationary and on-the-go unloading process for service units was tested. Obstacles were also considered in the simulation.

Since path of the primary unit is required by sub units this method can be classified as an offline approach. The proposals discussed so far concentrate on the primary unit or tractor. This proposal is unique as it is designed for sub units in the field. Also multiple robots as primary and secondary units are validated with obstacles. Kinematic restrictions of the trailer are not taken into consideration.

V. 3 DIMENSIONAL COVERAGE

A. Coverage in 3-Dimension using Genetic algorithm

Hameed [82] proposed coverage path planning for agricultural robots by modelling the field in 3 dimensions. Energy consumption models are studied to achieve optimal coverage with minimal fuel consumption. Two different approaches are discussed for determining an optimal driving angle thereby achieving coverage with reduced fuel consumption. Field boundary, operating width, vehicle speed, fuel cost, number of headland paths are given as inputs. The 3D representation of the field is obtained from digital elevation model (DEM) which consists of the elevation details of the field in a grid structure.

A genetic algorithm based approach was considered for finding an optimal driving angle which is the decision variable of this problem. A 2-dimensional model of the field is inputted to a genetic algorithm which finds an optimal driving angle for covering the field minimizing the number of tracks and headland turning cost. In the second stage the 2-D representation is combined with the information obtained from digital elevation model (DEM) thereby modelling the field in 3-diemsions. Fuel consumption models are used in this stage to analyse the driving angle determined in the first stage and further improve the solution.

In the second model, exhaustive search is performed for obtaining the driving angle. All possible driving angles from 1 to 180are tested. The 2D representation is obtained and then combined with DEM to obtain 3 D view of the field. The execution is tested by a material input operation simulation tool [83] by taking into account the capacity constraints. The 2D field representation, application rate, dosage of material, vehicle speed, turning radius, width, and tank capacity are given as input to the tool.

Special attention has been given to minimize the energy consumption by providing an optimal solution. The elevation of the field is considered. Power required is estimated by the parametric equation proposed by Froba and Funk [84]. Matlab® has been used to implement the model. Energy model is used to compare the fuel consumption in both 2D and 3D model of the field. A significant reduction in total operation time by minimizing the non-working distance is inferred from the results thereby achieving savings in operation cost and fuel consumption. The author also claims that it leads to an increase in yield since the driving over headland area is reduced which reduces degradation of soil fertility by avoiding soil compaction as a result of over driving.

Four different parameters obtained by varying the working width and tanker capacity were used in both the fields for simulation. High computational time is noticed since exhaustive search (179 executions) is done for finding the optimal driving angle. This restricts the use of this algorithm as an offline system. The results were compared by executing the scenarios in both 2D and 3D models of the field. An average of 6.5% reduction in energy consumption was observed when the algorithm was executed in 3D but at the cost of increase in operation time.

B. 3-dimensional coverage using slope data

Jin et al.,[85] demonstrated the efficiency of their algorithm which performs 3-dimesional coverage. Four criteria namely, field modelling, decomposition, coverage cost, and an optimization procedure were taken into consideration for the algorithm design. 2-D coverage is performed ignoring elevation changes and on the assumption that fields are flat. Further works by koostra et al., [86] prove that discrepancy in planar and topographic models have a huge economic impact. Data from the U.S. Department of Agriculture indicated that more than 48% of the cropland in United States has slopes in the field ranging from 2% to 10% which has been cited to justify the claim that 3-D coverage is preferred over 2-D coverage to achieve optimal coverage in reduced time. Tillage is the task for which coverage model has been implemented and validated. Soil erosion is the main factor in tillage, which is claimed to be reduced when coverage is performed in 3-dimensions [87].The elevation parameters are considered inn 3-D coverage which enables to generate an optimal coverage pattern for tillage. Techniques like tilling around the contour, increasing ridges control the flow pattern thereby reducing soil erosion [88].3-Dimensional model of the field helps to identify the slope pattern which enables in planning a tillage function to reduce soil erosion. Field modelling was done by obtaining analytical models from digital elevation models (DEM). In 2-D coverage headland turning cost was the only major cost factor whereas in 3-D coverage (for tillage) soil erosion cost and path curvature cost are also to be considered. The terrain was divided into sub-regions and different coverage patterns were followed for individual sub-regions depending upon the elevation. Compared to 2-D search, 3-D search space is huge, which increases the computational complexity of the optimization procedure.

For field modelling discrete evaluation model (DEM) was preferred over interpolation methods since they provide elevation information only at specified points. Slope and curvature calculations can be obtained from analytical models. DEM facilitate derivation of analytical models which are essential for cost calculations.

For approximation function, spline model is used since polynomial model are suited only for smooth functions and for large intervals the polynomial function has to be very large. Spline models also avoid the Runge's phenomenon for higher degrees. Integration of Dem data with B-form splines was implemented by tensor product splines.

Coverage cost was calculated considering the following factors: headland turning, soil erosion, and curvature of the path. Five types of turning patterns, keyhole, flat, U, hook and fishtail turn are taken into account for cost calculation. Swath width, vehicle turning radius headland width and the angle between swath and headland determine the trajectory length of each turning pattern. It is claimed that analysis of turning cost in 2-dimension is valid for turning cost calculation in 3-dimension. Soil erosion cost was formulated on the basis revised universal soil loss equation (RUSLE) model.

The curvature of the path greatly determine quantity of soil erosion. The concave and convex patterns of a curved path are analysed so as to minimize the occurrence of skipped areas. Switch-back turns are efficient in dealing with skipped areas but at the cost of increased time. The skipped areas were summed for approximation of cost.

The total cost was formulated by integration of the above cost factors. The various costs were normalized and the weighted average was considered to be the final cost function.

Field decomposition was achieved using divide and conquer strategy. Slope steep was the deciding factor for decomposing the field into sub regions with smooth boundaries. Other attributes include roughness of the ground and soil conditions. Based on the operator's preference different path planning strategies are adopted for each sub-region. Finding the optimal "seed curve" is claimed as the key to achieve 3D coverage path planning. Brute-force search is not useful for determining the seed curve since the search space is huge, so heuristic methods are adopted. Contour lines and field edge segments were considered as candidates for "seed curve".

The fields were classified based on their slopes as

- Flat area –regions with less than 3% slope where coverage planning is executed in 2-D
- Medium area- regions having slopes between 3% and 5% - 2D or 3D coverage is executed based on the terrain
- Steep area- regions with slops above 5% where 3-D panning is applied

Weights were set for the cost functions and the coverage solution obtained is claimed to be similar to a farmer's practical solution. Both 2-D and 3-D coverage was applied to the fields to compare the performance. Overall the 3-D coverage algorithm achieved 22 percent savings in cost combining turning, erosion and skipped area costs (10.3 percent +24.7 percent +81.2 percent).

Compared to the 3-D algorithm discussed in 5.1 this algorithm considers the percentage of slope from the DEM which is a unique factor that determines the efficiency of algorithms proposed to achieve coverage in 3-Dimension. Classifications of regions according to slopes and applying different algorithm accordingly for each sub-region also increase the overall efficiency and minimize cost to achieve coverage. Skipped areas are left to be optimized in future.
Kinematics and dynamic compatibilities such as vehicle speed, turning radius and angle are not considered while validating the algorithm.

VI. CONCLUSION AND FUTURE SCOPE

Path planning has been a challenging task for researchers working towards automation in various fields. Coverage path planning increases the complexity in achieving that goal by inducing various constraints to be satisfied. We have focused on algorithms that have been proposed so far to achieve coverage in Agriculture. Most of the earlier works were focused on simulating the proposed algorithms to validate the solution. Recently, researchers focus on real time data to validate their proposals. We have started by defining coverage path planning and have outlined the advancements in coverage algorithms in various field of application. In depth survey has been made on algorithms that focus on achieving coverage in agriculture. Section x described the various proposals that modelled the farm in 2-dimensions and achieved coverage. The decomposition strategy, algorithm technique and validation of the algorithm in real time field have been discussed in detail. More recently, researchers are focusing on modelling the field terrain as 3-dimension to achieve a more practical solution. Such proposals were discussed in section x. 3-Dimensional coverage algorithms are found to be more practical to be tried out in real time. The algorithms are compared based on the decomposition technique, vehicle parameters, type of autonomous robot, validation of the algorithm and the number of obstacles considered while testing the algorithm. Most of them have taken real time field data to test the efficiency. A drawback is they are validated in simulation. Only a few are compared with human performance to validate their efficiency. A recent achievement in coverage is modelling the field in 3-Dimensions to obtain the search space. The solution generated by 3-D coverage is more practical and feasible when compared to the solution generated by an algorithm performing coverage in 2-dimensions. This survey would serve as a starting point for researchers aiming to find a solution for coverage in 3-Dimensions.

REFERENCES

[1] Hu Y, Yang SX., "A knowledge based genetic algorithm for path planning of a mobile robot"'. In: Proceedings of the 2004 IEEE, international conference on robotics & automation, New Orleans USA , pp. 4350–4355, 2004

[2] T. Lozano-Perez, M.A. Wesley, "An algorithm for planning collision-free paths among polyhedral obstacles", ACM Communications, Vol. 2, pp. 959–962, 1979

[3] S.M. LaValle, "Planning Algorithms", Cambridge University Press, pp. 130–131, 2006.

[4] J.H. Reif, Z. Sun, "An efficient approximation algorithm for weighed region shortest path problem, Algorithmic and Computational Robotics: New Directions, A.K. Peters, pp. 191–203, 2001

[5] Z.L. Cao, Y. Huang, E.L. Hall, "Region filling operations with random obstacle avoidance for mobile robotics", Journal of Robotic Systems" Vol 5, Issue 2, pp.87–102, 1988

[6] M. Bosse, N. Nourani-Vatani, J. Roberts, Coverage algorithms for an underactuatedcar-like vehicle in an uncertain environment, in: Proc. IEEE Int.Robotics and Automation Conf., 2007, pp. 698–703.

[7] P. Atkar, A.L. Greenfield, D.C. Conner, H. Choset, A. Rizzi, Uniform coverage of automotive surface patches, The International Journal of Robotics Research Vol 24, Issue 11, pp 883–898, 2005

[8] M. Ollis, A. Stentz, First results in vision-based crop line tracking, in:Proc. Conf. IEEE Int. Robotics and Automation, Vol. 1, pp. 951–956, 1996

[9] M. Ollis, A. Stentz, Vision-based perception for an automated harvester, in: Proc. IEEE/RSJ Int. Intelligent Robots and Systems IROS'97. Vol. 3, pp. 1838–1844, 1997

[10] F. Yasutomi, M. Yamada, K. Tsukamoto, Cleaning robot control, in: Proc. Conf. IEEE Int Robotics and Automation, pp. 1839–1841, 1988.

[11] [E.U. Acar, H. Choset, Y. Zhang, M. Schervish, Path planning for robotic demining: robust sensor-based coverage of unstructured environments and probabilistic methods, International Journal of Robotics Research. Vol. 22, Issue 7, pp. 441–466, 2003.

[12] S. Hert, S. Tiwari, V. Lumelsky, A terrain-covering algorithm for an auv, Autonomous Robots , pp 91–119, 1996.

[13] Z.L. Cao, Y. Huang, E.L. Hall, Region filling operations with random obstacle avoidance for mobile robotics, Journal of Robotic Systems Vol 5, Issue 2, 87–102, 1988.

[14] D. MacKenzie and T. Balch, Making a clean sweep: Behavior based vacuuming, in: AAAI Fall Symposium, Instationating Real-World Agents, 1996.

[15] J. Palacin, T. Palleja, I. Valganon, R. Pernia, J. Roca, Measuring coverage performances of a floor cleaning mobile robot using a vision system, in: Proceedings of the 2005 IEEE International Conference on, Robotics and Automation, 2005.ICRA 2005. pp. 4236–4241.

[16] D. Gage, Randomized search strategies with imperfect sensors, in: Proc. SPIE Mobile Robots VIII, Boston, MA (September 1993) pp. 270–279.

[17] T. Balch, The case for randomized search, in: Workshop on Sensors and Motion, IEEE International Conference on Robotics and Automation, San Francisco, CA (May 2000).

[18] H. Choset,Coverage for robotics—a survey of recent results, Annals of Mathematics and Artificial Intelligence 31 (2001) 113–126.

[19] EnricGalceran, Marc Carreras, A survey on coverage path planning for robotics, Robotics and Autonomous systems 61 (2013) 1258-1276.

[20] H. Moravec and A. Elfes, High resolution maps for wide angles sonar, in: IEEE Int. Conf. on Roboticsand Automation (1985).

[21] A. Elfes, Sonar-based real-world mapping and navigation, IEEE J. Robotics Autom. 3 (1987) 249–265.

[22] J.S. Oh, Y.H. Choi, J.B. Park, Y. Zheng, Complete coverage navigation of cleaning robots using triangular-cell-based map, IEEE Transactions on Industrial Electronics 51 (3) (2004) 718–726.

[23] A. Zelinsky, R.A. Jarvis, J.C. Byrne and S. Yuta, Planning paths of complete coverage of an unstructured environment by a mobile robot, in: Proceedings of International Conference on Advanced Robotics, Tokyo, Japan (November 1993) pp. 533–538.

[24] O. Khatib, Real-time obstacle avoidance for manipulators and mobile robots, Internat. J. Robotics Res. 5 (1986) 90–98.

[25] J. Barraquand and J.-C.Latombe, "Robot Motion Planning: A Distributed Representation Approach", International Journal of Robotics Research Vol. 10 No.6, pp628-649, 1991.

[26] R.A. Jarvis and J.C. Byrne, "Robot Navigation: Touching, Seeing and Knowing", Proceedings of 1st Australian Conference on Artificial Intelligence, November 1986.

[27] V. Shivashankar, R. Jain, U. Kuter, D. Nau, Real-time planning for covering an initially-unknown spatial environment, in: Proceedings of the Twenty- Fourth International Florida Artificial Intelligence Research Society Conference, 2011.

[28] Y. Gabriely, E. Rimon, Spiral-stc: an on-line coverage algorithm of grid environments by a mobile robot, in: Proc. IEEE Int. Conf. Robotics and Automation, ICRA'02, Vol. 1, 2002, pp. 954–960.

[29] E. Gonzalez, O. Alvarez, Y. Diaz, C. Parra, C. Bustacara, Bsa: a complete coverage algorithm, in: Proc. IEEE Int. Conf. Robotics and Automation ICRA 2005, 2005, pp. 2040–2044.

[30] Y.-H. Choi, T.-K.Lee, S.-H.Baek, S.-Y. Oh, Online complete coverage path planning for mobile robots based on linked spiral paths using constrained inverse distance transform, in: Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems IROS 2009, 2009, pp. 5788–5793.

[31] T.-K. Lee, S.-H.Baek, Y.-H.Choi, S.-Y. Oh, Smooth coverage path planning and control of mobile robots based on high-resolution grid map representation, Robotics and Autonomous Systems 59 (10) (2011) 801–812.

[32] L. Hodgkin, A.F. Huxley, A quantitative description of membrane current and its application to conduction and exitation in nerve, Journal of Physics London 117 (1952) 500–544.

[33] C. Luo, S. Yang, A bioinspired neural network for real-time concurrent map building and complete coverage robot navigation in unknown environments, IEEE Transactions on Neural Networks 19 (7) (2008) 1279–1298.

[34] X. Qiu, J. Song, X. Zhang, S. Liu, A complete coverage path planning method for mobile robot in uncertain environments, in: Proc. Sixth World Congress Intelligent Control and Automation WCICA 2006, Vol. 2, 2006, pp. 8892–8896.

[35] L. Paull, S. Saeedi, H. Li, V. Myers, An information gain based adaptive path planning method for an autonomous underwater vehicle using sidescan sonar, in: 2010 IEEE Conference on Automation Science and Engineering, CASE, 2010, pp. 835–840.

[36] L. Paull, S. Saeedi Gharahbolagh, M. Seto, H. Li, Sensor driven online coverage planning for autonomous underwater vehicles, in: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS, 2012, pp. 2875–2880.

[37] J.C. Latombe, Robot Motion Planning, Kluwer Academic Publishers, 1991.

[38] H. Choset, K. Lynch, S. Hutchinson, G. Kantor, W. Burgard, L. Kavraki, S. Thrun, Principles of Robot Motion: Theory, Algorithms, and Implementation, The MIT Press, 2005.

[39] F.P. Preparata and M.I. Shamos, Computational Geometry: An Introduction (Springer-Verlag, Berlin,1985) pp. 198–257.

[40] J. VanderHeide and N.S.V. Rao, Terrain coverage of an unknown room by an autonomous mobile robot, Technical report ORNL / TM-13117, Oak Ridge National Laboratory, Oak Ridge, TN (1995).

[41] H. Choset, E. Acar, A. Rizzi and J. Luntz, Exact cellular decompositions in terms of critical points of morse functions, in: IEEE International Conference on Robotics and Automation, San Francisco, CA (2000).

[42] H. Choset and P. Pignon, Coverage path planning: The boustrophedon decomposition, in: Proceedings of the International Conference on Field and Service Robotics, Canberra, Australia (December1997).

[43] E.U. Acar, H. Choset, A.A. Rizzi, P.N. Atkar, D. Hull, Morse decompositions for coverage tasks, International Journal of Robotics Research 21 (4) (2002) 331–344.

[44] J. Milnor, Morse Theory, Princeton University Press, 1963.

[45] E.U. Acar, H. Choset, A.A. Rizzi, P.N. Atkar, D. Hull, Morse decompositions for coverage tasks, International Journal of Robotics Research 21 (4) (2002) 331–344.

[46] G. Reeb, Sur les points singuliersd'uneforme de Pfaff complètementintégrableoud'une function numérique, ComptesRendus de l'Académie des Sciences 222 (1946) 847–849.

[47] S.C. Wong, B.A. MacDonald, A topological coverage algorithm for mobile robots, in: Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems, IROS 2003, Vol. 2, 2003, pp. 1685–1690.

[48] Z.J. Butler, A.A. Rizzi, R.L. Hollis, Contact sensor-based coverage of rectilinear environments, in: Proc. IEEE Int Intelligent Control/Intelligent Systems and Semiotics Symposium, 1999, pp. 266–271.

[49] L. Xu, Graph Planning for Environmental Coverage, Ph.D. Thesis, Carnegie Mellon University, 2011.

[50] V.J. Lumelsky, S. Mukhopadhyay, K. Sun, Dynamic path planning in sensor based terrain acquisition, IEEE Transactions on Robotics and Automation 6 (4) (1990) 462–472.

[51] T.-S. Lee, J.-S.Choi, J.-H.Lee, B.-H. Lee, 3-d terrain covering and map building algorithm for an auv, in: Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems IROS 2009, 2009, pp. 4420–4425.

[52] P.N. Atkar, H. Choset, A.A. Rizzi, E.U. Acar, Exact cellular decomposition of closed orientable surfaces embedded in r3, in: Proc. ICRA Robotics and Automation IEEE Int. Conf, Vol. 1, 2001, pp. 699–704.

[53] P. Cheng, J. Keller, V. Kumar, Time-optimal uav trajectory planning for 3D urban structure coverage, in: IEEE/RSJ International Conference on, Intelligent Robots and Systems, 2008, IROS 2008, 2008, pp. 2750–2757.

[54] Kanae Tanigaki, Tateshi Fujiura, Akira Akase, Junichi Imagawa, Cherry-harvesting robot, Computers and Electronics in Agriculture 63 (2008) 65-27

[55] Y.Yanwei, Z.Xiaochao, Z.Huaping, Apple harvesting robot picking path planning and simulation, International conference on Information Engineering and Computer Science, 2009, pp. 1-4

[56] E.J. Van Henten, J.Hemmin, B.A.J. Van Tuijl, J.G. Kornet, J. Bontsema, Collision-free Motion Planning for a Cucumber Picking Robot, Biosystems Engineering (2003) 86 (2), 135-144

[57] A. J. Scarfe, R. C. Flemmer, H. H. Bakker and C. L. Flemmer, Development of An Autonomous Kiwifruit Picking Robot, Proceedings of the 4th International Conference on Autonomous Robots and Agents, Feb 10-12, 2009. pp 380-384.

[58] Yael Edan, Member, IEEE, Dima Rogozin, Tamar Flash, and Gaines E. Miles, IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, VOL. 16, NO. 6, DECEMBER 2000 pp 831-834

[59] Feng Qingchun, Zheng Wengang, Qiu Quan,Jiang Kai, Guo Rui, Study on Strawberry Robotic Harvesting System, IEEE International Conference on Computer Science and Automation Engineering (CSAE), 2012 pp 320-324

[60] G. Muscato, M. Prestifilippo, Nunzio Abbate and Ivan Rizzuto, A prototype of an orange picking robot: past history, the new robot and experimental results, Industrial Robot: An International Journal 32/2 (2005) pp 128-138

[61] Ibrahim A. Hameed, Dionysis Bochtis, and Claus A. Sørensen, An Optimized Field Coverage Planning Approach for Navigation of Agricultural Robots in Fields Involving Obstacle Areas, Int J Adv Robotic Sy, 2013, Vol. 10, 231:2013, pp 1-9

[62] Whitley D (1994) A Genetic Algorithm Tutorial. Statistics and Computing 4(2): 65-85.

[63] Jung Won Kang, Si Jong Kim and Myung Jin Chung, Path Planning for Complete and Efficient Coverage Operation of Mobile Robots. In Proceedings of the 2007 IEEE International Conference on Mechatronics and Automation. August 5-8, 2007, Harbin, China.

[64] Simon X. Yang and ChaominLuo.A Neural Network Approach to Complete Coverage Path Planning. IEEE Transactions on Systems, Man,and Cybernetics-Part B:Cybernetics, 2004,34(1):718-725.

[65] Yan Ma, Hua-bo Liu and Shu-huaXu. Path Planning Design for Cleaning Robot. Machinery and Electronics, 2008 (7): 64-67.

[66] A.E.F. Ryerson and Q. Zhang. "Vehicle Path Planning for Complete Field Coverage Using Genetic Algorithms". Agricultural Engineering International: the CIGR Ejournal. Manuscript ATOE 07 014. Vol. IX. July, 2007. pp 1-11

[67] Lin, H.-S., J. Xiao, and Z. Michalewicz. 1994. Evolutionary algorithm for path planning inmobile robot environment. In Proc. IEEE Conference on Evolutionary Computation, 1:211-216. Piscataway, NJ, USA: IEEE.

[68] Hwang Y.K., Ahuja, N. (1992). Gross Motion Planning.A Survey,.ACMComputing Surveys, vol. 24, no. 3, pp. 219-290, (1992).

[69] D.D. Bochtis, C.G. Sorensen, S.G. Vougioukas, Path planning for in-field navigation-aiding of service units, Computers and Electronics in Agriculture 74 (2010) 80-90

[70] K. Zhou, A. Leck Jensen, C.G. Sørensen, P. Busato, D.D. Bothtis, Agricultural operations planning in fields with multiple obstacle areas, Computers and Electronics in Agriculture 109 (2014) pp 12–22

[71] Toussaint, G.T., 1983. Solving geometric problems with the rotating calipers. In:Proc. 2nd IEEE Mediterranean Electrotechnical Conference (MELECON 1983),pp. 1–4.

[72] Dorigo, M., Gambardella, L.M., 1997. Ant colony system: a cooperative learning approach to the traveling salesman problem. IEEE Trans. Evol. Comput. 1 (1),53–66.

[73] Timo Oksanen and Arto Visala, Coverage Path Planning Algorithms for Agricultural Field Machines, Journal of Field Robotics 26(8), 651–668 (2009) pp 651-668

[74] Felkel, P., &Obdrzalek, S. (1998, April). Straight skeleton implementation. In Proceedings of Spring Conferenceon Computer Graphics, Budmerice, Slovakia (pp. 210– 218).

[75] Bochtis, D.D., Oksanen, T., Combined coverage path planning for field operations, 7th European Conference on Precision Agriculture, Wageningen, the Netherlands.

[76] I. Rekleitis, A. New, E. Rankin, H. Choset, Efficient boustrophedon multirobot coverage: an algorithmic approach, Annals of Mathematics and Artificial Intelligence 52 (2009) 109–142. http://dx.doi.org/10.1007/s10472-009-9120-2.

[77] N. Hazon, G. Kaminka, Redundancy, efficiency and robustness in multi-robot coverage, in: Proceedings of the 2005 IEEE International Conference on, Robotics and Automation, 2005, ICRA 2005, 2005, pp. 735–741.

[78] C. Luo, S. Yang, A real-time cooperative sweeping strategy for multiple cleaning robots, in: Proceedings of the 2002 IEEE International Symposium on, Intelligent Control, 2002, 2002, pp. 660–665.

[79] K. Easton, J. Burdick, A coverage algorithm for multi-robot boundary inspection, in: Proceedings of the 2005 IEEE International Conference on, Robotics and Automation, 2005, ICRA 2005, 2005, pp. 727–734.

[80] M.A. Batalin, G.S. Sukhatme, Spreading out: a local approach to multi-robot coverage, in: Proceedings of the 6th International Symposium on Distributed Autonomous Robotics Systems, 2002, pp. 373–382.

[81] Guoyu Zuo, Peng Zhang, and Junfei Qiao, Path Planning Algorithm Based on Sub-Region for Agricultural Robot, 2010 2nd International Asia Conference on Informatics in Control, Automation and Robotics, pp 197-200

[82] D.D. Bochtis, C.G. Sorensen, S.G. Vougioukas, Path planning for in-field navigation-aiding of service units, Computers and Electronics in Agriculture 74 (2010) 80-90

[83] A. Hameed, Intelligent Coverage Path Planning for Agricultural Robots and Autonomous Machines on Three-Dimensional Terrain, J Intell Robot Syst (2014) 74:965–983

[84] Hameed, I.A., Bochtis, D.D., Sørensen, C.G., Vougioukas, S.: An object oriented model for simulating agricultural in-field machinery activities. Computers and Electronics in Agriculture. 81(1), 24–32 (2012)

[85] Fröba, N., Funk, M.: TeilzeitspezifischeDieselbedarfskalkulationbeiArbeiten in der Außenwirtschaft. KTBL-Arbeitsblatt: Landtechnik und Pflanzenbau Nr. 0255 'BenötigteTraktormotornennleistungbeilandwirtschaftlichenArbeiten' (N. Fröba, 1995)(in Germany) (1995)

[86] Jian Jin and Lie Tang, Coverage Path Planning on Three-Dimensional Terrain for Arable Farming, Journal of Field Robotics 28(3), 424–440 (2011) pp 424-440

[87] Koostra, B. K., Stombaugh, T., Mueller, G. T., & Shearer, A. S.(2006, July). Evaluating the effect of terrain on field area measurements. In 2006 ASABE Annual Meeting. ASABE Paper No. 061045. St. Joseph, MI: ASABE.

[88] Van Doren, A. C., Stauffer, S. R., & Kidder, H. E. Effect of contour farming on soil loss and runoff. Soil Science Society of America Proceedings, 15, 413–417,1950.

[89] Wendt, G. (1998). Guidelines for the use of the revised universal soil loss equation (RUSLE) version 1.06 on mined lands, construction sites, and reclaimed lands. Denver,CO: Peabody Western Coal Company.

[90] Gesch, D. B. (2007). The National Elevation Dataset.In D.Maune (Ed.), Digital elevation model technologies and applications: The DEM users manual, 2nd ed. (pp. 99–118). Bethesda, MD: American Society for Photogrammetry and Remote Sensing.