Motion Planning for Autonomous Landmine Detection and Clearance Robots

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***Abstract*—Demining or mine clearing is the process of detecting and removing land mine from an area. Uncleared landmines represent a major humanitarian and economic threat in over 70 countries. Its victims suffer from permanent disability if not killed and require horrific expensive care. Also, the cost of the land, roads, and underground resources that remains useless. Clearing mines is very dangerous work. The majority of demining work is still carried out manually using metal detectors and prodders. For every 5,000 mines that are removed, one person is killed and two people are injured. Over the years there has been considerable interest within the scientific and engineering communities in the application of advanced technologies to improve the safety and efficiency of this work. In this paper a motion-planning algorithm to enable landmine detection and clearing robots to systematically scan a minefield, detect landmines and clear it is presented. The algorithm works on two steps; (1) generate the driving tracks that can be used to scan the minefield area, and (2) connect these tracks using Dubins' path in order to generate a continues and complete trajectory which can be used for the robot's navigation. The inputs to the algorithm are the coordinates of the outer boundaries of the minefield's vertices, the operating width of the robot, the minimum turning radius of the robot/autonomous vehicle, the required (or optimized) driving angle in the field, and the robot's entrance point to the minefield. The output is a trajectory that consists of the coordinates of a number of headland paths connected using Dubins' curves and a set of parallel tracks covering the entire minefield area connected using Dubins' curves. The resultant trajectory enables the robot to scan the minefield area in the shortest time in a way that prevents missing any landmine by scanning the entire field area. It also enables the robot to work fully autonomous with minimal or without human intervention at all and therefore it dramatically reduces risks of workplace injury and maximize operation efficiency.**

Keywords—UN; World War II; Egypt; landmine accidents; Dubins' curve; optimization; autonomous; landmine detection;

I. Introduction

It is estimated that there are 110 million active landmines distributed over 70 countries. About 100,000 mines are removed each year. At this rate it would take 1,100 years to clear all the landmines in the world assuming no new mines are laid. More than 2,000 people are involved in landmine accidents every month - one person every 20 minutes. Around 800 of them die while the rest are maimed. Clearing mines is very dangerous work, for every 5,000 mines that are removed one person is killed and two are injured. The most common mines are cheap but it can cost 50 times as much to remove each one [1-2]. In addition to the financial cost of removing mines, there are many other loses due to the land, roads and underground resources that cannot be used, and the costs of treating its victims. Egypt still has the most landmines in its land: 23 million spread over 25,000 km^2 although 10 million have been cleared from the western desert, the Sinai desert, and Suzie Canal over the years. Over the past 25 years, landmines victimized about 7,923 people, including 3,200 dead and 4,723 injured, according to local and international statistics. Landmines persist as a significant problem for civilians long after a conflict has finished and have a major impact on post-conflict reconstruction. They are invisible (as they are often buried or camouflaged) and indistinguishable and as a result cause terror in the civilian population. Because of the threat of landmines, a sizable part of Egypt's arable land, approximately 10% of the total cultivatable area is rendered useless [3].

The detection of buried landmines is traditionally performed through exhaustive searching by humans using some basic tools. Potential mines are located using a metal detector to locate metal fragments such as the firing pin of the landmine and/or by feeling for mounds or depressions that are caused by the laying of the mines or by the subsequent settling of the ground. These potential mines are then investigated further through manual probing. Actually, many deminers probe the entire ground area regardless of whether they have found a potential mine [4]. In contrast to manual methods involving humans, the trend is to find automated solutions for the demining process. Two major aspects are investigated: 1) How to reduce the de-miner casualties by use of robots and 2) Improvement of mine sensing technologies for accurate detection [5]. To prevent the number of casualties due to manual mine clearance, mobile robots can be used for detection and mapping of the minefield region. Recent approaches for the use of mobile robots in landmine detection include a swarm of lightweight robots which is light enough not to make the mine explode [6-9], larger and heavier robots (i.e., Mine Breaker 2000) [10], and legged robots [11-13].

In this paper, a coverage path planning approach to enable mine clearance robots to autonomously and systematically navigate throughout a minefield is presented. The inputs to the algorithm are; (1) the outer boundaries of the field in Universal Transverse Mercator (UTM) coordinate system (m) or in degrees (^{o}) ordered in clockwise direction, (2) the operating width, W, of the mine clearance robot (m), (3) the driving angle, θ, in the minefield (^{o}) which determines the required direction of the parallel field tracks, and (4) the robot initial position. The output is a list of waypoints representing a number of headland paths, field parallel tracks and the turning paths connecting these tracks. The resulting trajectory stored in the form of a KML file for representation in Google maps.

The paper is organized as follows; an introduction to social and economical impact of landmines and the current technology of landmine clearance robots is given in Section I. Section II field coverage algorithm for autonomous operation of landmine clearance robots is presented. Results and the discussion of results are given in Section III. Concluding remarks are presented in Section IV.

II. Coverega Path Planning for Autonous Operations of Landmine Clearneance robot

Autonomous humanitarian demining is one of the few robotic tasks that require complete coverage of unstructured environment. A complete coverage algorithm is a path planning technique that generates a trajectory that allows the robot to pass over all points in the environment in a systematic way, avoiding obstacles. Although scanning a minefield is much simpler than in agriculture where an autonomous vehicle or a robot has to drive in rows in order to minimize crop damage, the same driving pattern used in crop fields can be used in minefields in order to facilitate the cooperation between a swarm of such lightweight clearance robots and to the mine mapping process [14-16].

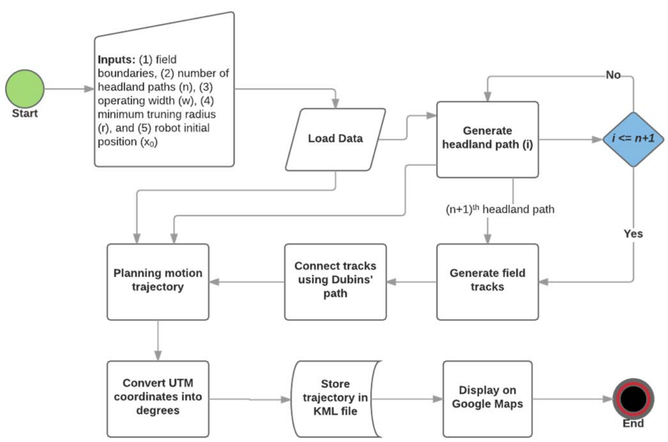

Fig. 1. Mission planning for landmine clearnace robot.

The algorithm starts by uploading the minefield's outer boundary in either Universal Transverse Mercator (UTM) coordinates or in degrees. The algorithm starts by generating a number of headland paths, n, that is required to be cleared first in order to provide the clearance robot enough space for executing safe headland turnings between different tracks. The number of headland paths is chosen as a function of the operating width and the minimum turning radius of the autonomous vehicle. Field tracks are then generated to cover the remaining minefield area after the headland paths. Dubins' curve is used to generate headland turnings between parallel tracks. The Dubins' path gives the shortest path joining two oriented points that is feasible for the adopted robot/vehicle model [17]. The generated trajectory is finally converted into degrees and stored in a KML file for easy display on Google maps. A Flow diagram for the generation of a complete trajectory for autonomous operation of landmine clearance robot is shown in Fig. 1.

A. Headland generation

The field headland area is obtained by offsetting the boundary inward by a width equal to the multiplication of the number of headland paths, n, and the operating width, W, of the landmine clearing robot/vehicle. The distance from the field boundaries to the first headland pass is half the operating width, $W/2$, while the distance between the first headland path and subsequent headland paths equal to a full operating width, W. The remaining field body after headland area is determined by an inner boundary created at $W/2$ distance from the last headland path [18-19].

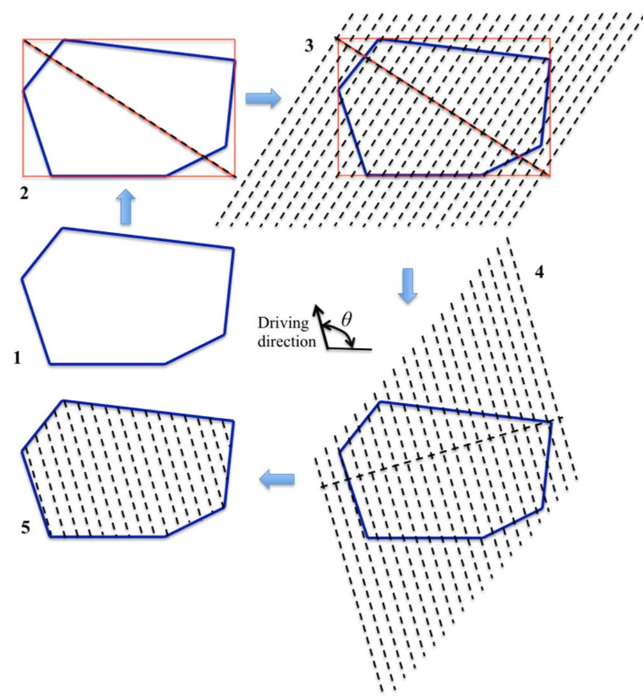

Fig. 2. Generation of parallel field tracks to cover the minefield body.

B. Work tracks generation

Track generation refers to the process of generating parallel tracks to cover the field body after headland area. The tracks are generated parallel to a reference driving line with an angle, θ, with the easting axis [18]. The minimum-bounding box (MBB) of the field body is first obtained. MBB is the smallest enclosing box of a set of points. It provides symmetry and simplicity of dealing with fields of complex shapes and ensures full coverage with the generated work tracks. One diagonal of the MBB is used as a reference line. The reference line is divided into a number of segments of length W. A set of lines is generated perpendicular to the reference line and passing through the end point of each segment. The MBB and the generated lines are rotated until generated parallel tracks become parallel to the required driving direction in the minefield. Driving direction is a line with an angle θ with the x-axis (i.e., with easting direction). Intersection points between the generated parallel lines and field's last headland path, n+1, are obtained. These lines can then be used as driving tracks to cover the minefield body after headland paths. Tracks generation process is illustrated in Fig. 2.

Fig. 3. Experimental field located at [30.857567, 28.892248], North Coast, Matrouh, Egypt.

TABLE I. COORDINATES OF OUTER FIELD BOUNDARIES

Point number	Coordinates	
	Northing	*Easting*
1	30.862082	28.891637
2	30.859490	28.895476
3	30.857015	28.899202
4	30.849955	28.893152
5	30.853907	28.886957

C. Coonecting field tracks using Dubins' curve

In the work of Dubins [17], the smooth shortest path for fixed initial and final positions and orientations has been obtained geometrically. Hameed et al [20] explored the use of Dubins path to find the optimal path for connecting field tracks in agriculture. Hameed [21] used Dubins path for generating a smooth, continues, and complete path for driving an autonomous line-marking robot in a football field. Dubins' path in this paper is used to connect the robot tracks over the headland area. To comply with safety constraints, turnings over headland area should be short, smooth and continues. Given two points in the plane, the initial and final points, P_i, and P_f, respectively. Each point is associated with its own orientation angle, ϑ_i , and ϑ_f which defines the prescribed direction of motion of each point. The combination of (P_i, θ_i) and (P_f, θ_f) are known as the initial and final configurations. The task is to find the shortest smooth path from P_i to P_f such that it starts and ends with the directions of motions θ_i and θ_f, respectively. Dubins showed that the shortest feasible path connecting P_i and P_f consists of exactly three path segments of a sequence CCC or CSC class paths, where C for circle is an arc of radius r, and S for straight is a line segment which can then be decomposed into a set of six candidate paths [17]. The optimum path was then found by explicitly computing all paths on the list and then extract the shortest path from the set.

D. Dectection and clearance scenario

A potential covering scenario to that meets safety constraints is that the robot starts its demining task from an initial position located outside the field boundaries. It then drives around the minefield (for n headland paths) to clear an area enough for executing safe turnings between field tracks. The robot then drives into work tracks following a default order starting from track 1 to track m. An optimization algorithm can also be used to order field tracks in a manner that reduces operation time and/or travelled distance over headland area [14].

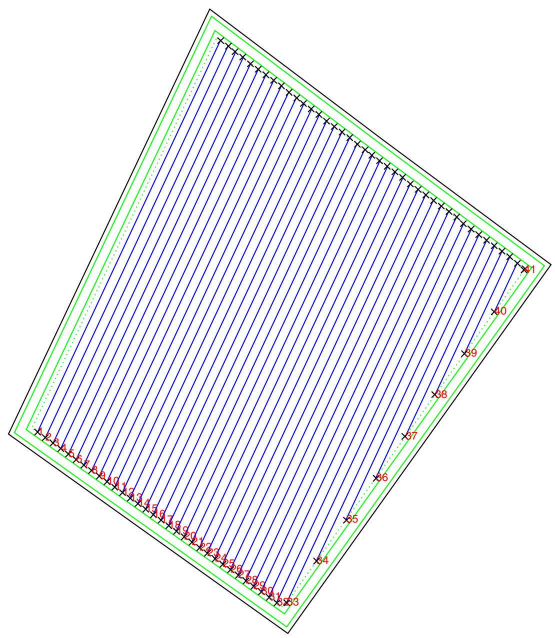

Fig. 4. Coverage plan for 2 headland path, 20 m operating width and 65o driving angle with the *Easting* direction, 42 tracks are geneated to cover the field body after headland area.

III. SIMULATION RESULTS

Locations of mines in Egypt are divided into two main field; landmine fields in Western Desert and landmine fields in Eastern Desert. The Western Desert mine fields extend from *Al Alamain* up to the Egyptian-Libyan borders with a depth of more than 40 km from the Mediterranean coast. Landmines planted in these fields vary in type and size depending on the troops involved in combat operations [3]. They are spread in ten fields. The coastal strip on both sides of *Alexandria-Matrouh* road is one of the oldest and most dangerous landmine fields in Egypt. Manual clearance of landmines is expensive and dangerous because of: (1) the lack of accurate records of the mine fields, (2) the increased sensitivity of the mines since they have been implanted for more than 60 years in WWII, (3) shifting of mines due to erosion and floods, (4) shifting of sands which buried mines deeply and makes detection more difficult, and (5) very slow process and the high cost associated with training and accommodation in remote areas. Therefore the autonomous clearance of mines can be considered as an effective way for mine clearance in terms of speed, risk and cost.

A. *Experimental landmine field*

A real-world landmine field located at [30.857567N, 28.892248E] is used for testing the algorithm presented in this paper. The field, shown in Fig. 3, has an area of 81.15 ha. Coordinates of outer-field boundary in clockwise direction are shown in Table I. These coordinates are converted into UTM coordinates in m before processing.

B. *Generation of the field coverage course*

The coverage plan is generated for n=2 headland paths, W=20 m operating (i.e., implement) width, and for a driving angle θ=65°. The resultant coverage plan is shown in Fig. 4 where 41 tracks are generated.

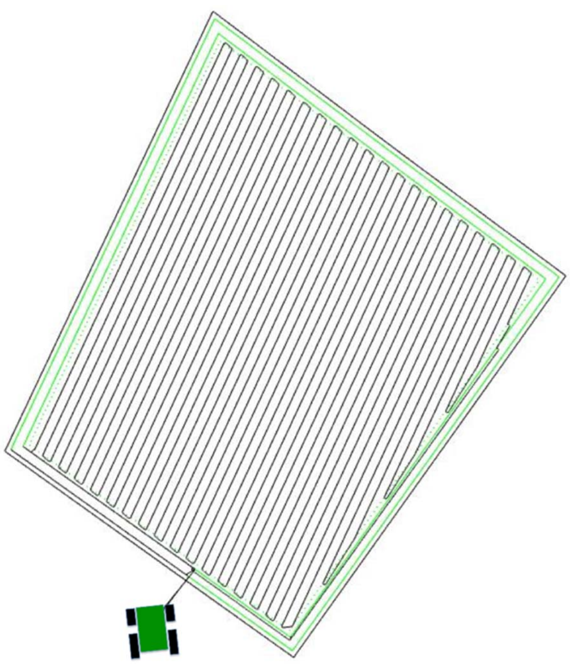

Fig. 5. Complete trajectory using Dubins' curve.

C. *Dubins' path for complete trajectory generation*

Dubins' path is used to generate a complete, continues and smooth trajectory for the robot passing through the coverage plan points. The robot initial position and heading angle are assumed to be (x_0, y_0)=(680728.4, 3.41456.3) with a heading angle of 95.7° with *Easting* axis. The resulting trajectory is shown in Fig. 5. The trajectory coordinates are converted back into degrees and saved in a KML file for easy display on Google maps. KML (i.e., Keyhole Markup Language) is an XML based file format used to display geographic data in an Earth browser such as Google Earth, Google Maps, and Google Maps for mobile. The trajectory can be used for testing using a robot simulator before driving in the real field.

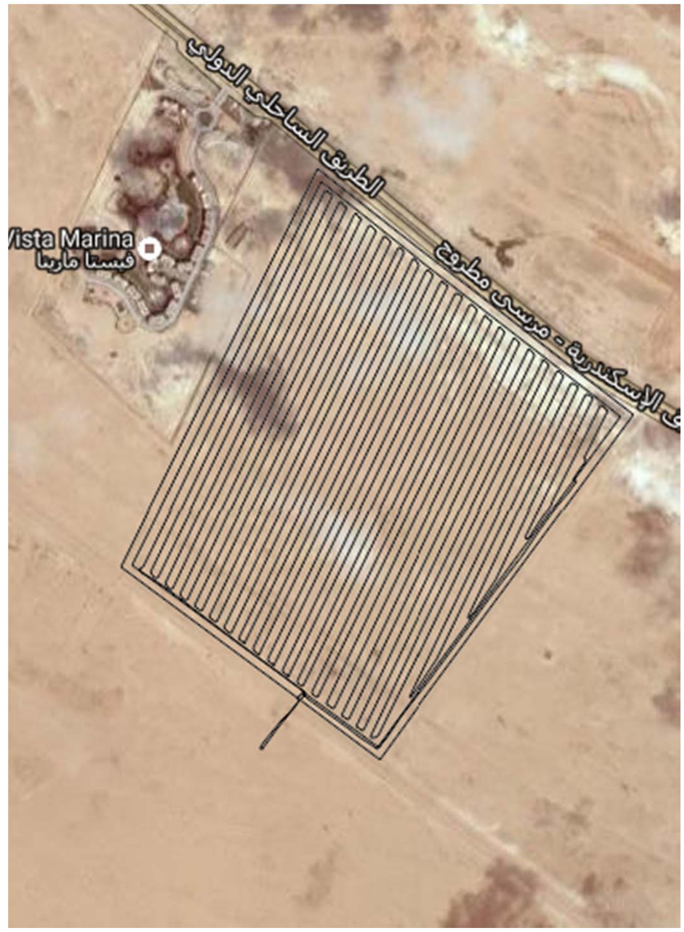

Fig. 6. The robot trajectory displayed on Google maps (visit shorten url: goo.gl/uYRvep for an online version of the map).

IV. Summary

A field coverage algorithm to enable mine detection and clearance robot to cover large minefields is presented. The driving pattern enables the robot to systematically cover the minefield in a manner that increases efficiency and reduces risks. Dubins' path is used to connect various components of the driving pattern by generating a smooth, complete and continuous trajectory, which can be used for guidance, navigation and control of the autonomous landmine detection and clearance robots. Using this approach enables these types of robots to provide fast and accurate clearing with no missing areas without any fatigue around the clock. It reduces labor costs, expensive training of manual deminers and improves their working conditions and safety. It reduces risks of injury and losing life and hence reduces direct medical costs, costs of being a way from the work for long time, rehabilitation and insurance. Rapid landmines clearance can help several parties to get access to resources that are important for the local development and creating new jobs and opportunities for local communities. As a future work, the landmine field will be represented in 3D and a trajectory that considers the topological characteristics of the minefield will be generated. Also having multiple autonomous landmine detection and clearance robotic systems capable of working together under the control of one operator to cooperatively perform such complex tasks and mission is under consideration.

REFERENCES

[1] Landmines – Trial of terror. New Internatiionalist magazine, issue 294, September 1997.

[2] International Committee of the Red Cross (ICRC), https://www.icrc.org/en/war-and-law/weapons/anti-personnel-landmines.

[3] Landmines in Egypt, State Information Service http://www.sis.gov.eg/Story/106?lang=en-us.

[4] K.M. Dawson-Howe, and T.G. Williams, "The detection of buried landmines using probing robots," *Robotics and Autonomous Systems*, vol. 23, no. 4, pp. 235-243, 1998.

[5] S. Gowda, "*Autonomous robotic landmine detection, mapping and avoidance*," MSc thesis, University of Texas at Arlington, May 2015.

[6] R. Cassinis, G. Bianco, A. Cavagnini, and P. Ransenigo, "Strategies for navigation of robot swarms to be used in landmines detection," In *Porceedings of the Third IEEE European Workshop on Advanced Mobile Robots* (Eurobot'99), pp. 211-218, 1999.

[7] J.D. Nicoud, "Vehicles and robots for humanitarian demining," *Industrial Robot*, vol. 24, no. 2, pp. 164-168, 1997.

[8] J. Nicoud, and P. Machler, "Robots for anti-personnel mine search," *Control Engineering Practice*, vol. 4, no. 4, pp. 493—498, 1996.

[9] H. Najjaran, and A.A. Goldenberg, "Landmine detection using an autonomous terrain ‐ scanning robot," *Industrial Robot: an international journal*, vol. 32, no. 3, pp. 240-247, 2005.

[10] Mine Breaker 2000, http://www.nato.int/sfor/engineers/mines/mine-breaker/minebreak.htm.

[11] G. Royston, and C. Jacobus, "Walking robots for mine-field detection," In: *Proceedings of Autonomous Vehicles in Mine Countermeasures Symposium, Monterey*, CA, pp. 8.86-8.99, 1995.

[12] P. Gonzalez de Santos, E. Garcia, J. Estremera, and M.A. Armada, "DYLEMA: Using walking robots for landmine detection and location," *International Journal of Systems Science*, vol. 36, no. 9, pp. 545-558, 2005.

[13] M. A. Armada, J. Cobano, E. Garcia and P. Gonzalez de Santos, "Configuration of a legged robot for humanitarian demining activities," In: *Proceedings of the IARP International Workshop on Robotics and Mechanical Assistance in Humanitarian Demining (HUDEM2005)*, Tokyo, Japan, pp. 131-135, 2005.

[14] I.A. Hameed, D.D. Bochtis, and C.G. Sørensen, "Driving Angle and Track Sequence Optimization for the Operational Path Planning using Genetic Algorithms," *Applied Agricultural Engineering*, vol. 27, no. 6, pp. 1077-1086, 2011.

[15] I.A. Hameed, D.D. Bochtis, C.G. Sørensen, and S. Vougioukas, "An Object Oriented Model for Simulating Agricultural in ‐ field Machinery Activities," *Computers and Electronics in Agriculture*, vol. 81, no. 1, pp. 24-32, 2012.

[16] I.A. Hameed, D.D. Bochtis, C.G. Sørensen, A.L. Jensen, and R. Larsen, "Optimized Driving Direction Based on a Three ‐ dimensional Field Representation," *Computers and Electronics in Agriculture*, vol. 91, pp. 145-153, 2013.

[17] L.E. Dubins, "On Curves of Minimal Length with a Constraint on Average Curvature, and with Prescribed Initial and Terminal Positions and Tangents," American Journal of Mathematics, vol. 79, no. 3, pp. 497–516, 1957.

[18] I.A. Hameed, D.D. Bochtis, C.G. Sørensen, and M. Nørremark, "Automated generation of guidance lines for operational field planning," *Journal of Biosystems •Engineering*, vol. 107, no. 4, pp. 294-306, 2010. •

[19] I.A. Hameed, "Intelligent coverage path planning for agricultural robots and autonomous machines on three-dimensional terrain," *Journal of Intelligent & Robotic Systems*, Springer Netherlands (http://dx.doi.org/10.1007/s10846-013-9834-6), •vol. 74, pp. 965–983, 2013. •

[20] I.A. Hameed, A. la Cour-Harbo, and K.D. Hansen, "Task and motion planning for selective weed control using a team of autonomous vehicles," In: *Proceedings of the 13th IEEE International Conference on Control, Automation, Robotics and Vision*, pp. 1853-1857, 2014.

[21] I.A. Hameed, "Path planning for line marking robots using 2D Dubins' path," In: *Proceedings of the 2nd International Conference on Advanced Intelligent Systems and •Informatics (AISI'16)*, Cairo, Egypt, 2016.