SOUTH CAROLINA HONORS COLLEGE SENIOR THESIS PROPOSAL

Depth-Weighted Path Planning for Autonomous Lakebed Coverage with an ASV

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INTRODUCTION & THESIS STATEMENT

Coverage path planning problem is the task of generating a path for a sensor-laden robot to follow such that the entirety of the environment is observed. A common example of coverage path planning is an autonomous robot vacuum [1]. Other applications include lawn mowing [2], and window cleaning [3]. Additionally, harmful algal blooms are becoming more prevalent globally and, specifically, in South Carolina over the last 2-3 decades [4]. Coverage path planning in conjunction with autonomous surface vehicles can efficiently survey algal blooms in any given lakebed. In one of the first works on coverage path planning [2], Cao et al. carefully defined the what a robot must do to successfully cover an environment. The requirements are the following:

1. Robot must move through all the points in the target area covering it completely.
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.

As Enric Galceran notes in his recent survey on coverage path planning for robotics [5], it is not always possible to optimize all of these criteria; thus, sometimes priority must be set when developing a coverage path planning algorithm. For certain applications, these criteria are straightforward and well-defined; however, in other applications, it is not as clear how to optimize Cao's coverage requirements.

One popular coverage technique is the boustrohpedon pattern laid out by Howie Choset [6] which mimics the path of an ox plowing a field. While this technique may not be truly optimal, it yields a very simple path which guarantees coverage. In 2014, Xu et al. [7] improved the boustrophedon coverage for aerial applications by ensuring the robot can return to its starting location without overlap. They also showed that this technique is asymptotically optimal, i.e. the path length decreases asymptotically to the shortest possible as the area of the space to cover increases with respect to the sensor footprint. More recently, boustrophedon coverage was adapted for vehicles operating under Dubins constraints [8] and for multi-robot coverage [9]. While many coverage planners assume the robot maintains a constant altitude (this is a reasonable assumption for drones), Galceran [10] developed a system for underwater coverage which breaks the space into multiple parts by depth and performs boustrophedon coverage over each area independently to avoid excessive overlap in the covered area.

In this project, we build upon [10] and use techniques from differential geometry to take full advantage of the fact that the sensor footprint is larger in deeper waters. Following Moser's construction in [11], we transform the space in such a way that volume elements are proportional to the sensor width. We can then use a conventional path planning technique like boustrophedon coverage which assume a constant depth and project the path back into the original space. We also plan to explore various such transformations to optimize other criteria such as the sharpness of turns.

Overall, the contributions of this project will be

1. A novel method for coverage path planning of a body of water with variable depths.
2. Proof that our method is able to guarantee coverage and perform more efficiently than state of the art methods which assume there is little variation in depth.
3. Experimental verification of our method on Lake Murray using an autonomous surface vehicle (ASV).

METHODOLOGY

We will start by analyzing existing coverage planning algorithms to see where they use the assumption that water bodies have a constant depth. We will develop multiple possible methods which do not have that assumption, then compare their theoretical efficiencies. In parallel, we will develop a path planning system with obstacle avoidance capabilities and deploy it on a robotic boat capable of measuring depth, position and other important data using a radar, GPS, and Inertial Measurement Unit (IMU). We will combine these two directions by using the autonomous boat, most likely a Jetyak, to execute the coverage plan we generate, measure the area covered, and record the depth of the lake at each position.

EXPECTED OUTCOME & POTENTIAL SIGNIFICANCE

Our primary objective is to develop a mathematically sound method for coverage path planning which utilizes the variable sensor footprint due to depth variation. In order for this technique to be considered successful, we must prove that the technique guarantees coverage and is reasonably efficient. On its own, this part of the project will be significant in the applied math community because we will establish a way to solve the coverage problem using techniques from differential geometry.

Our secondary objective is to implement the system onboard an autonomous boat. As part of this objective, we will also develop an obstacle avoidance system using a radar sensor to ensure the boat will not be damaged during experiments. Once we have experimental verification of the system, we hope to publish the work at a robotics conference. Since the data we gather has experimental value even outside this thesis, we hope the data will be useful for other research for years to come.

In completing this project, we hope to learn more about how to develop autonomous robots and to learn how to apply complex mathematics, including differential geometry, to practical projects.

ANNOTATED BIBLIOGRAPHY

This is the full bibliography, but we only annotate [5], [6], [8], [10], [11].

[1] F. Yasutomi, M. Yamada, and K. Tsukamoto, "Cleaning robot control," in *Proc. IEEE International Conference on Robotics and Automation (ICRA)*, vol. 3, 1988, pp. 1839–1841. DOI: `10.1109/ROBOT.1988.12333`.

[2] Z. L. Cao, Y. Huang, and E. L. Hall, "Region filling operations with random obstacle avoidance for mobile robots," *Journal of Robotic Systems*, vol. 5, no. 2, pp. 87–102, 1988. DOI: `10.1002/rob.4620050202`.

[3] M. Farsi, K. Ratcliff, J. P. Johnson, C. R. Allen, K. Z. Karam, and R. Pawson, "Robot control system for window cleaning," in *Proc. American Control Conference (ACC)*, vol. 1, 1994, 994–995 vol.1. DOI: `10.1109/ACC.1994.751894`.

[4] A. Lewitus, L. Schmidt, L. Mason, J. Kempton, S. Wilde, J. Wolny, B. Williams, K. Hayes, S. Hymel, C. Keppler, and A. Ringwood, "Harmful algal blooms in south carolina residential and golf course ponds," *Population and Environment*, vol. 24, pp. 387–413, 2003. DOI: `10.1023/A:1023642908116`.

[5] E. Galceran and M. Carreras, "A survey on coverage path planning for robotics," *Robotics and Autonomous Systems*, vol. 61, no. 12, pp. 1258–1276, 2013. DOI: `10.1016/j.robot.2013.09.004`,

This paper provides a survey and summary of the state of research in coverage path planning at the time of publication. Galceran and Carreras cover successful methods, achievements, field applications, and recent breakthroughs in coverage path planning. This paper helped to determine where to begin with our research on the topic. Galceran provides a logical, chronological, comprehensive review of methods and achievements in coverage path planning in the field of robotics. Starting with a discussion of the classical boustrophedon decomposition due to Choset, the paper progressed to more advanced ideas like cellular decompositions, grid-based methods, neural-network-based coverage, and graph-based coverage. Additionally, Galceran and Carreras review 3D-coverage and multi-robot methods. A review of the surrounding literature is pivotal for understanding and progressing efficiently through a research problem. Primarily, this paper laid the groundwork of our knowledge about the coverage problem in robotics.

[6] H. Choset, "Coverage of known spaces: The boustrophedon cellular decomposition," *Autonomous Robots*, vol. 9, pp. 247–253, 2000. DOI: `10.1023/A:1008958800904`,

This paper describes coverage planning in the presence of obstacles and presents what is now the most common technique, boustrohpedon coverage. This technique allows a robot to perform coverage of a non-rectangular space with polygonal obstacles (note that real obstacles may be approximated as polygons). It works by dividing the space to be covered into multiple cells and performing a lawn-mower pattern within each cell. The decomposition into cells occurs by moving a vertical line over the space and splitting cells when an obstacle starts or combining cells whenever an obstacle ends. These cells correspond to the edges of the Reeb graph which describes the topology of the space. The paper compares its method to trapezoidal decomposition and shows that trapezoidal decomposition often results in a finer decomposition which can reduce efficiency. We plan to use a variation of this method in a transformed space to produce a path which guarantees coverage and takes advantage of depth variation.

[7] A. Xu, C. Viriyasuthee, and I. Rekleitis, "Efficient complete coverage of a known arbitrary environment with applications to aerial operations," *Autonomous Robots*, vol. 36, pp. 365–381, 2014. DOI: `10.1007/s10514-013-9364-x`.

[8] J. S. Lewis, W. Edwards, K. Benson, I. Rekleitis, and J. M. O'Kane, "Semi-boustrophedon coverage with a dubins vehicle," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 5630–5637. DOI: `10.1109/IROS.2017.8206451`,

This paper extends boustrohpedon coverage to vehicles with Dubins constraints, e.g. vehicles which cannot turn in place and must move forward while turning, like an automobile. The paper provides a reduction of the exact cover problem to the coverage problem to verify that the coverage problem is NP-hard and, thus, not tractible for real-world scenarios. Rather than solving the problem exactly, the paper uses an approximate solver for the travelling salesperson problem to generate a near optimal coverage path under Dubins constraints. The paper presents experimental verification that the method is able to produce results with comparable efficiency using less computation time. Being able to perform coverage on a Dubins vehicle is critical to our project because the autonomous boats will obey the same constraints, and an attempt to plan without taking the Dubins model into account will result in a path which cannot be executed accurately.

[9] N. Karapetyan, K. Benson, C. McKinney, P. Taslakian, and I. Rekleitis, "Efficient multi-robot coverage of a known environment," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2017, pp. 1846–1852. DOI: `10.1109/IROS.2017.8206000`.

[10] E. Galceran and M. Carreras, "Efficient seabed coverage path planning for asvs and auvs," in *Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 2012, pp. 88–93. DOI: `10.1109/IROS.2012.6385553`,

This paper builds on the 2000 paper by Howie Choset by applying boustrophedon coverage path planning to underwater robotic coverage with varying depth. While this paper deconstructs the space into cells based on obstacle placements as in the Choset paper, it also breaks the space apart into regions with similar depth. While the original formulation of boustrophedon coverage assumed a constant sensor footprint, in underwater coverage the footprint varies as depth changes. By performing coverage differently at different depths, this paper's method is able to perform more efficiently than assuming a constant depth. The paper also describes detailed experiments which compare their method to the traditional boustrophedon method. We improve upon the concept presented by Galceran by considering the changes in depth to be continuous rather than discrete.

[11] J. Moser, "On the volume elements on a manifold," *Transactions of the American Mathematical Society*, vol. 120, pp. 286–294, 1965. DOI: 10.1090/S0002-9947-1965-0182927-5,

This paper is the basis for our idea of transforming the space in such a way that we can use traditional coverage planning to work with variable depth. While we only care about a two-dimensional space with a depth function which is inversely related to sensor width, Moser works more generally in a closed connected n-dimensional manifold. Moser's theorem gives a construction of a smooth diffeomorphism between two manifolds provided they have the same total volume. In our case, we use one manifold to have the normalized reciprocal of the depth as the volume elements of one manifold and 1 as the volume elements of the other. This way, the diffeomorphism between the two equalizes the sensor footprint throughout the space.

TIMELINE

The group meets weekly with Dr. Ioannis Rekleitis and Dr. Joshua Cooper virtually on Mondays at 5:30 p.m. EST. At the weekly meetings, we discuss the progress through the week and lay out expectations for the following week. The following table lays out our schedule for the remaining weeks, starting from the week of February 8, 2021.

Date	**Topic**
Week 1	Set up radar onboard the autonomous boat
Week 1–2	Implement obstacle avoidance for boat
Week 2	Field trial to test obstacle avoidance with a simple path
Week 1–3	Implement Moser's symplectomorphism construction [11] and generate path using this method
Week 3–4	Experimentally check the completeness of Moser's construction in a simulated environment
Week 3–4	Export generated path in a way that can be used for navigation by the autonomous boat
Week 4	Field trial using Moser's construction on Lake Murray
Week 5–7	Implement randomly generation of symplectomorphisms and an optimization criterion
Week 7–8	Experimentally check completeness of random symplectomorphism method
Week 8	Field trial using random symplectomorphism method
Week 6–8	Write mathematical proof of completeness for Moser's construction and the randomly generated symplectomorphism method
Week 8–9	Analyze data and evaluate results (the results will also be analyzed after each field trial)
Week 9–10	Prepare final presentation
Week 9–10	Prepare draft of final paper
April 19	Final Presentation (tentative)