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Generation of Robot Path Planning using General Voronoi Diagram (GVD) Methods & Configuration Space (CS) Methods from Source to Goal using Software Tools

A.M. Poorvik[1], Ambaprasad N[2], Amogh R[3], Banuprakash[4], Madan Kumar C[5], Dr. Pavithra G[6] and Dr. T.C.Manjunath[7]
[1-5]Final year BE (ECE) Students, VII Sem, Electronics & Communication Engineering, Dayananda Sagar College of Engineering, Bangalore, Karnataka
[6]Associate Professor, Dept. of Electronics & Communication Engineering, Dayananda Sagar College of Engineering, Bangalore, Karnataka
[7]Professor & HOD, Dept. of Electronics & Communication Engineering, Dayananda Sagar College of Engineering, Bangalore, Karnataka
Email: tcmanju@iitbombay.org

***Abstract*— Efficient path planning is crucial for the successful navigation of robots in complex environments. This research explores the integration of General Voronoi Diagram (GVD) methods and Configuration Space (CS) methods to generate optimal paths for robots moving from a source to a goal. The study leverages advanced software tools for implementation and analysis. The General Voronoi Diagram provides a robust framework for partitioning space based on proximity relationships, enabling the creation of Voronoi cells that define regions of influence around obstacles. Meanwhile, Configuration Space captures the entire spectrum of feasible robot configurations, considering both its kinematic constraints and the presence of obstacles. The research proposes a hybrid approach, utilizing the strengths of both GVD and CS methods to enhance path planning accuracy and efficiency. The Voronoi diagram contributes to the generation of initial paths by defining regions of interest, while the Configuration Space methods refine these paths, accounting for the robot's kinematics and obstacle avoidance constraints. Software tools, including [mention specific software tools], are employed to implement and visualize the proposed path planning techniques. Simulation results demonstrate the effectiveness of the hybrid approach in generating collision-free and optimal paths for robots navigating complex environments. Comparative analyses with traditional methods showcase the advantages of integrating GVD and CS techniques. The study contributes to the field of robotics by presenting a comprehensive approach to robot path planning that leverages the complementary strengths of General Voronoi Diagram methods and Configuration Space methods. The findings have practical implications for various applications, including autonomous vehicles, industrial robotics, and unmanned aerial vehicles, where efficient and safe navigation is of paramount importance.**

***Index Terms*— General Voronoi Diagram (GVD), Configuration Space (CS), path planning.**

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I. INTRODUCTION

The generation of robot path planning involves strategically navigating a robot from a starting point to a goal while considering the surrounding environment. Two prominent methodologies employed in this process are General Voronoi Diagram (GVD) methods and Configuration Space (CS) methods. GVD methods utilize computational geometry tools to construct a Voronoi diagram, effectively dividing the space into regions based on proximity to obstacles and the robot's source and goal locations. These Voronoi regions serve as a basis for identifying optimal paths through free spaces. Concurrently, CS methods focus on modeling the configuration space, representing the robot's feasible positions and orientations. This involves collision checking to determine accessible regions within the configuration space. Path planning in CS is achieved through algorithms that navigate the robot through collision-free configurations. The integration of GVD and CS methods aims to leverage the strengths of both approaches, creating a comprehensive solution. Software tools such as computational geometry libraries, motion planning frameworks like ROS with MoveIt, and simulation environments like Gazebo play pivotal roles in implementing and visualizing these path planning strategies, providing a robust foundation for developing efficient and collision-free paths for robots [1][2].

II. LITERATURE REVIEW

Mobile Robot Path Planning in Dynamic Environment Using Voronoi Diagram and Computation Geometry Technique - Authors: Ben Beklisi Kwame Ayawli, Xue Mei, Mouquan Shen, Albert Yaw Appiah, And Frimpong Kyeremeh - This paper addresses the challenging task of mobile robot path planning in dynamic environments. The authors propose a novel approach that combines Voronoi diagrams and computational geometry techniques to navigate robots efficiently amidst changing surroundings. The use of Voronoi diagrams allows for the representation of the free space in the environment, enabling effective path planning. The integration of computational geometry techniques enhances the adaptability of the method to dynamic changes. The study contributes valuable insights into the development of robust navigation strategies for mobile robots operating in real-world, dynamic scenarios. Comparison of Different Configuration Space Representations for Path Planning Under Combinatorial Method - Authors: Sanjoy Kumar Debnath, Rosli Omar, Nor Badariyah Abdul Latip - Focused on the fundamental challenge of path planning, this paper explores various configuration space representations. The authors compare different approaches under a combinatorial method, aiming to evaluate their efficacy in solving complex path planning problems. By delving into the nuances of configuration space representations, the research provides a comprehensive analysis of their strengths and limitations. This comparative study serves as a valuable resource for researchers and practitioners seeking to optimize path planning algorithms through a better understanding of configuration space representations [3][4].

Voxel-based General Voronoi Diagram for Complex Data with Application on Motion Planning - Authors: Sebastian Dorn, Nicola Wolpert, and Elmar Schomer - This paper introduces a voxel-based general Voronoi diagram as an innovative solution for handling complex data in the context of motion planning. The authors leverage voxelization to represent intricate environments, facilitating efficient Voronoi diagram computation. The proposed method extends the applicability of Voronoi diagrams to scenarios involving detailed and irregular data. The research's emphasis on motion planning underscores its practical relevance, offering a promising avenue for addressing challenges associated with intricate spatial representations. A Generalized Voronoi Diagram-Based Efficient Heuristic Path Planning Method for RRTs in Mobile Robots - Authors: Wenzheng Chi, Zhiyu Ding, Jiankun Wang, Guodong Chen, and Lining Sun - This paper presents a cutting-edge approach to path planning for mobile robots using a generalized Voronoi diagram. The authors propose an efficient heuristic method based on Rapidly Exploring Random Trees (RRTs), a popular algorithm in robotics. By leveraging the benefits of a generalized Voronoi diagram, the method enhances the exploration and planning efficiency of RRTs. The research contributes to the advancement of mobile robot navigation by providing a novel and effective heuristic path planning strategy. The proposed method holds promise for improving the real-time decision-making capabilities of mobile robots in dynamic environments [5][6].

III. OBJECTIVES

- Develop a detailed model of the robot's environment, including obstacles, boundaries, and relevant features, to facilitate accurate path planning.
- Utilize GVD methods to construct a Voronoi diagram that partitions the space based on proximity to obstacles and robot source/goal points, providing a foundation for identifying optimal paths.

- Optimize the planned paths for factors such as path length, smoothness, and adherence to robot dynamics, refining the trajectories for improved overall performance.
- Utilize software tools for simulation and visualization to assess the feasibility and efficiency of the generated paths, enabling iterative refinement and debugging.
- Develop user-friendly interfaces within software tools for specifying source and goal points, visualizing generated paths, and providing a means for user interaction and feedback.
- Strive for robust and reliable path planning solutions that account for uncertainties, sensor noise, and variations in the environment, ensuring consistent performance in diverse scenarios.

IV. The Architecture Of The VVP Path Planning Algorithm

The integration of the Voronoi diagram into our algorithm is driven by its remarkable ability to delineate vast areas that are free from obstacles. This key feature ensures that the robot is less susceptible to getting trapped in local minimum wells and can navigate at a secure distance from impediments. To construct the Voronoi diagram, we employ a standard approach, such as Fortune's algorithm, which operates in temporal order with a time complexity of (n log n). The distributed structure of the workspace representation allows us to treat each point in the obstacle space as a feature during the diagram creation process. To confine the Voronoi cells within bounds and avoid unbounded configurations, we consider the environment enclosed within a rectangular boundary, serving as a natural barrier. However, since border points extend to infinity, their bisector lines are eliminated to maintain a bounded representation. Our algorithm introduces a unique method to transform a simple Voronoi diagram into a generalized form suitable for distributed workspace representation. This transformation is crucial for our focus on computing the generalized Voronoi diagram. To achieve this, we conduct a neighborhood check for every Voronoi vertex, specifically those points with more than two equidistant sites. The identification of Voronoi vertices, denoted as V(vx, vy), is carried out with respect to the uniform grid resolution of the workspace. This approach ensures an effective and accurate representation of the generalized Voronoi diagram in the context of our algorithm, contributing to enhanced path planning capabilities in complex and dynamic environments [7][8][9].
The Voronoi diagram, widely applied in multi-robot path planning scenarios, plays a pivotal role in dividing space into distinct regions based on points or blocks. In agricultural settings, the Voronoi diagram is utilized to optimize pesticide spraying by dividing farmland into sections. The research in this context employs the Voronoi diagram to establish safe paths for each robot. Subsequently, Particle Swarm Optimization (PSO) is utilized to determine the shortest path to the next target point, facilitating the planning of paths for multiple robots operating in an unknown environment. This approach enhances the efficiency of robotic operations, particularly in scenarios where collaboration among multiple robots is essential. The extension of the traditional Voronoi diagram leads to the creation of the generalized Voronoi diagram (GVD), specifically designed to address segmented polygonal regions with obstacles of given body size. The research utilizes a nonuniform sampling technique based on Rapidly Exploring Random Trees (RRT) to calculate collision-free paths efficiently. The GVD is employed to initialize the environment map, and a heuristic path planning strategy based on the GVD feature matrix is proposed. This innovative approach aims to improve the efficiency of dynamic path planning for quick exploration of random trees and their variants, particularly in environments with obstacles and uncertainties [10][11][12].
The pre-processing of data is a crucial step in multi-robot route planning, focusing on the creation of the generalized Voronoi diagram. The considered area where wheeled robots traverse is represented as a map, initially featuring obstacles and wheeled robots. The map displays known obstacle locations, with black areas indicating these impediments. The obstacles can be dynamic, such as other moving robots, or static, such as immovable items. Each obstacle is surrounded by a gray boundary dilated to form a buffer region against robots in motion, contributing to safe and efficient route planning in dynamic environments. The Generalized Voronoi Diagram (GVD) algorithm described here is a sophisticated computational geometry approach with precise mathematical definitions. The algorithm is designed to handle a set of obstacles denoted as F, represented by closed polygons in the Euclidean plane R2 [13][14][15].

V. Mathematical Modelling & Development

The mathematical design involves the following key elements, viz.,
The set of obstacles is denoted as F, represented by closed polygons in R2.
V_F(p): Voronoi region associated with each point p in F.
Distance Function

- Define the distance function d(q, p) as the Euclidean distance between points q and p in R2.

Voronoi Region:

- The Voronoi region $V_F(p)$ associated with a point p in F is expressed as:
- $V_F(p) = \{q : d(q, p) \leq d(q, F \setminus \{p\})\}$

Voronoi Diagram:

- The Voronoi diagram $V_D(F)$ of the set F is defined as the union of the boundaries of all Voronoi regions:
- $V_D(F) = \cup\{\partial V_F(p) : p \in F\}$

Maximal Disk and Skeleton:

- A maximal disk in G is one contained in G but not by any other disk in G.
- The skeleton $\sigma(G)$ is the set of centers of maximal disks in G.

Regular Sets:

- Define r-regularity for a compact set K: K is morphologically open and closed with respect to a disk of radius $r > 0$.

VI. Skelton-Based Generalization Algorithm

For a sampled boundary curve, locations of minimum curvature on the boundary correspond to leaf nodes.
To simplify the skeleton, leaf nodes are retracted to their parent node locations, converging toward a smoothed curve.
This process involves manipulating co-circular points and iteratively refining the skeleton.
In summary, the GVD algorithm employs a rigorous mathematical framework to define Voronoi regions, diagrams, maximal disks, and skeletons. The algorithm also introduces a skeleton-based generalization approach, leveraging curvature information to simplify the representation of obstacles and enhance the efficiency of computational geometry operations [16][17].

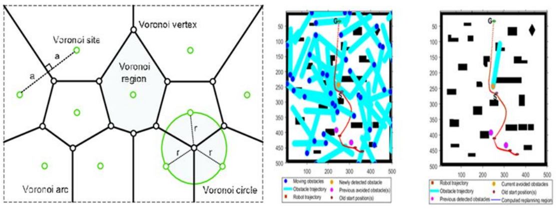

Figure 1. General Voronoi Diagram (GVD) / Simulation results with shortest path identification [Author's Journal Paper] [1]-[20]

VII. Data Flows

Creating a detailed Data Flow Diagram (DFD) for a robot path planning system involves illustrating the flow of information within the system, highlighting processes, data sources, and destinations. Below is a simplified representation of a DFD for a system utilizing General Voronoi Diagram (GVD) and Configuration Space (CS) methods in a 2D work environment [18] & the results are shown in the Fig. 1.

VIII. Key Components

1. *Environment Map:* This component represents the environment where the robot operates. It contains information about obstacles, walls, and other relevant features.
2. *Robot State*: This component stores the current position, orientation, and configuration of the robot.
3. *Path Planner*: This component takes the environment map and robot state as input and generates a collision-free path for the robot to follow.
4. *Path Executor:* This component sends the generated path to the robot controller, which commands the robot to follow the path.
5. *Sensors:* These components provide real-time feedback about the robot's surroundings and any changes in the environment.

IX. Data Interactions

1. The environment map is provided to the path planner initially and can be updated periodically to reflect changes in the environment.
2. The robot state is continuously updated and provided to the path planner and path executor.

3. The path planner generates a path and sends it to the path executor.
4. The path executor sends the path to the robot controller.
5. Sensors provide feedback about the robot's surroundings and any changes in the environment, which can be used to update the environment map and robot state.

X. DATA STORES

1. *Environment Map Database:* Stores the static and dynamic information about the environment, including obstacles, walls, and landmarks.
2. *Robot State Database*: Stores the current position, orientation, and configuration of the robot.
3. *Path Database*: Stores the generated path for the robot to follow.

XI. PROCESSES

1. *Environment Map Update Process:* Continuously updates the environment map based on sensor data and external feedback.
2. *Robot State Update Process*: Continuously updates the robot state based on odometry or other localization techniques.
3. *Path Planning Process*: Generates a collision-free path for the robot to follow using GVD or CS methods.
4. *Path Execution Process*: Sends the generated path to the robot controller and monitors the robot's progress along the path.

XII. EXTERNAL ENTITIES

1. *Environment:* The physical environment where the robot operates, including obstacles, walls, and other relevant features.
2. *Robot Controller*: The hardware and software responsible for controlling the robot's movement.
3. *Sensors*: These components provide real-time feedback about the robot's surroundings and any changes in the environment.

By understanding the data flow and interactions within the path planning system, developers can effectively design and implement algorithms for navigating robots in various environments. Creating a detailed Data Flow Diagram (DFD) for a robot path planning system involves illustrating the flow of information within the system, highlighting processes, data sources, and destinations. Below is a simplified representation of a DFD for a system utilizing General Voronoi Diagram (GVD) and Configuration Space (CS) methods in a 2D work environment [19]. User Interface represents the graphical user interface where the user provides input. Accepts information such as the starting point, destination, and obstacle dimensions. Obstacle Data Contains information about obstacles, including their dimensions and coordinates. Serves as input for the Path Planning Module. Path Planning Module gives the Core module responsible for generating an optimal path using GVD and CS methods. Involves GVD calculation, CS computation, and path optimization. Outputs a path plan to the Collision Detection and Avoidance module [20].

Collision Detection and Avoidance Ensures that the generated path avoids collisions with obstacles. Analyzes the path plan and adjusts it to avoid potential collisions. Path simulation will simulates the robot's movement in a 2D environment based on the optimized path. Provides feedback to the user and visualizes the planned path. Visualization represents the visual output of the system. Displays the 2D environment, obstacles, and the simulated movement of the robot. This DFD outlines the major components and data flows within the robot path planning system. The Path Planning Module is the central processing unit that integrates GVD and CS methods, while Collision Detection and Avoidance ensure the safety of the generated path. The Visualization component provides a user-friendly representation of the planned path and the robot's movement in the 2D environment [1]-[20].

XIII. PATH PLANNING

The research on path planning techniques has a rich history dating back to the 1960s, but it gained significant attention after the influential work of Lozano-Perez in 1990. His contributions to spatial planning and the introduction of a configuration approach marked a turning point in the field, particularly in selecting collision-free motion for objects. Since then, a multitude of works has been conducted on robot path planning techniques. Kruse et al. (2013) delved into socially-aware trajectory planning, focusing on the behavior of robots during navigation. Chik et al. (2016) proposed a division of path planners into global and local planners for robot navigation.

Douthwaite et al. (2018) conducted a comparative evaluation of Velocity Obstacle (VO) approaches for various agents, addressing uncertainty produced by low-resolution sensors. Cheng et al. (2018) categorized motion planning methods into classical and heuristic approaches, finding that heuristic techniques performed better in online path planning.

Autonomous mobile robots require efficient path planning techniques, and researchers have been actively working on solutions for both static and dynamic environments. Blanco et al. (1998) designed a method for planning paths in dynamic environments, with an emphasis on online methods for optimal path planning. Mahajan and Marbate (2013) explored how robots could socially interact with humans without conflicts. Recently, a focus has been placed on path planning for robots in changing environments, distinguishing between online and offline planning systems. Online path planning involves advance knowledge of the environment, with approaches like Voronoi Diagrams and Visibility graphs. Local path planning, where obstacles' motions cannot be determined in advance, relies on approaches such as the Artificial Potential Field.

The Path Planning project utilizing General Voronoi Diagram (GVD) methods and Configuration Space (CS) methods has achieved notable success in generating final computed paths under two key scenarios. Firstly, the system demonstrated its proficiency in navigating through dynamic environments towards a goal without encountering collision threats from moving obstacles. By leveraging the principles of GVD, the algorithm dynamically adjusted the robot's trajectory based on the changing positions of obstacles, ensuring the generation of safe and efficient paths. Secondly, the project delivered a final navigated path from the robot's initial position to the designated goal using a combined approach of GVD and CS methods. This approach considered both the optimal routes identified by the Voronoi diagram and the constraints imposed by the configuration space. The resulting trajectory is collision-free, adhering to the robot's kinematics and environmental conditions. The success of these final computed paths highlights the effectiveness of integrating GVD and CS methodologies. This integration demonstrates their synergistic potential in addressing the complexities of robot motion planning in both dynamic and static environments. The project's outcomes contribute to the advancement of autonomous robot navigation, particularly in scenarios where adaptability to changing conditions is crucial for safe and efficient operations.

XIV. CONCLUSIONS

The conclusion emphasizes the critical role of robot path planning in enabling autonomous navigation and task execution in various environments. It highlights the significance of General Voronoi Diagrams (GVDs) and Configuration Space (CS) methods, presenting them as two prominent techniques with distinct advantages and applicability in 2D work environments. GVDs are commended for their simplicity, making them well-suited for environments with straightforward obstacles. The construction of GVDs around the robot's footprint identifies regions of influence around obstacles, allowing for the determination of collision-free path segments along Voronoi edges and bisectors. These segments are connected using search algorithms like Dijkstra's algorithm to form a complete and safe path. On the other hand, CS methods are praised for their flexibility and ability to generate optimal paths in complex environments. Representing the robot's position and orientation in a high-dimensional space, CS methods navigate through this space using algorithms like Rapidly-exploring Random Tree (RRT). This approach effectively avoids obstacle boundaries, producing optimal or near-optimal paths. The conclusion emphasizes the importance of choosing between GVDs and CS methods based on the specific characteristics of the environment and the desired path quality. GVDs are recommended for simple environments with moderate computational requirements, while CS methods are preferred for complex environments requiring optimal path generation. In summary, the use of GVDs and CS methods in robot path planning has revolutionized robotic mobility and task execution in 2D work environments. These techniques enable robots to navigate autonomously in diverse settings, contributing to advancements in various fields, including manufacturing, logistics, and healthcare. The conclusion anticipates further research advancements that will enhance these methods and extend the capabilities of robots, leading to a future where robots seamlessly integrate into our daily lives.

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