COMPUTATIONALLY-EFFICIENT PATH PLANNING ALGORITHMS IN OBSTACLE-RICH ENVIRONMENTS BASED ON VISIBILITY GRAPH METHOD

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For my beloved mother and father, Salbiana Hashim and Abdul Latip MD Yatim.
For their encouragement…
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ABSTRACT

Path planning purpose is to find a collision-free path in a defined environment from a starting point to a target point. It is one of the vital aspects in enhancing an autonomy of a robot. Current studies have been focused on developing path planning algorithms to satisfy the criteria of path planning namely minimum path length, low computation time and complete, i.e., it gives positive result if a path is available or negative if otherwise. There are several existing path planning methods such as Visibility Graph (VG), Voronoi Diagram (VD), Potential Fields (PF) and Rapidly-Exploring Random Tree (RRT). Among those, VG is superior in terms of producing a path with the least length and completeness. However, VG has a drawback due to the fact that its computation time will increase in obstacle-rich environments. Moreover, as a path planned by VG is piece-wise linear which has sharp turns at corners, it is infeasible due to the kinematic constraints of a robot. Kinematic constraints limit the degree of freedom of the robot. In order to address the high computation time, an improved VG called Iterative Equilateral Spaces Oriented Visibility Graph (IESOVG) has been developed by reducing the number of obstacles used for path planning. IESOVG manipulates the size of the equilateral space to determine the obstacles used in path planning and consequently produces a free-collision path in considerably shorter time. On the other hand, to overcome the kinematic constraint of a car-like robot, Proportional controller, Proportional-Derivative (PD) controller and Bezier curves have been implemented to ensure that the resulting paths are feasible. As a result of the proposed methods, computation time of conventional VG has been improved by 97 %. The implementation of PD controller may contribute to path planning software development for autonomous car industry.

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ABSTRAK

Tujuan perancangan laluan adalah untuk mencari jalan yang bebas dari perlanggaran di dalam persekitaran, dari titik permulaan ke titik sasaran. Ianya adalah salah satu aspek yang penting dalam meningkatkan autonomi robot. Kajian semasa banyak memberikan fokus untuk membangunkan "*path planning algorithm*" bagi memenuhi kriteria perancang jalan iaitu menghasilkan jalan yang minimum, memerlukan masa pengiraan yang rendah dan "algorithm" yang lengkap, iaitu, memberikan hasil positif jika terdapat laluan dan hasil negatif jika tidak. Terdapat beberapa kaedah perancang laluan seperti "*Visibility graph*" (VG), "*Voronoi Diagram*" (VD), "*Potential fields*" (PF) dan "*Rapidly-Random Tree*" (RRT). Di antaranya, VG lebih unggul dari segi menghasilkan jalan yang minimum dan "*algorithm*" yang lengkap. Namun, VG mempunyai kelemahan iaitu masa pengiraannya akan meningkat apabila persekitaran dipenuhi dengan halangan. Selain itu, laluan yang dirancang oleh VG adalah "*piece wise linear*" dan mengandungi sudut yang tajam, susah untuk dilalui oleh robot kerana kekangan kinematik robot. Kekangan kinematik mengehadkan kebebasan robot untuk bergerak. Untuk mengatasi masa pengiraan yang tinggi, VG yang dipanggil "*Iterative Equilateral Space oriented Visisbility Graph*" (IESOVG) telah dibangunkan dengan mengurangkan bilangan halangan yang digunakan untuk merancang laluan. IESOVG memanipulasi saiz ruang sama untuk menentukan halangan yang digunakan dalam merancang laluan dan mampu menghasilkan laluan yang bebas dari pelanggaran dalam masa yang lebih singkat. Malah, untuk mengatasi kekangan kinematik robot seperti kereta, "*Propotional Controller*" (P), "*Proportional-directives Contoller*" (PD) dan "*Bezier Curve*" telah diaplikasikan untuk memastikan laluan yang dihasilkan mudah dilalui. Hasil daripada kaedah yang dicadangkan, masa pengiraan VG konvensional telah meningkat sebanyak 97%. PD boleh menyumbang kepada pembangunan perisian perancangan jalur untuk industri kereta autonomi.

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LIST OF SYMBOLS AND ABBREVIATIONS

%	-	Percentage
2-D	-	Two Dimensional
3-D	-	Three Dimensional
ACO	-	Ant Colony Organization
AUV	-	Autonomous Underwater Vehicles
BFS	-	Breadth-First Search
BLOVL	-	Base Line Oriented Visibility Graph
BMW	-	Bavarian Motor Works
CD	-	Cell Decomposition
CGAL	-	Computational Geometry Algorithm Library
CM	-	Cost Matrix
C-spaces	-	Configuration Spaces
d	-	Orientation Error
DEM	-	Digital Evaluation Map
DVG	-	Dynamic Visibility Graph
ESOVG	-	Equilateral Spaces Oriented Visibility Graph
E_x	-	Heading Error
f(n)	-	Forward Cost
GA	-	Genetic Algorithm
GUI	-	Graphical User Interface
h(n)	-	Backward Cost
IESOVG	-	Iteration Equilateral Spaces Oriented Visibility Graph
LEA	-	List Expanding Algorithm
LIDAR	-	Light Detection and Ranging
m	-	Metre

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m/s	-	Meter per seconds
m^2	-	Meter square
m^3	-	Metre per cube
O	-	Obstacles
^{o}	-	Degree
Open CL	-	Open Computing Language
Open MP	-	Open Multiprocessing
OVG	-	Oriented Visibility Graph
P-Controller	-	Proportional Controller
PD-Controller	-	Proportional and Derivatives Controller
PF	-	Potential Fields
PID controller	-	Proportional-Integral-Derivatives Controller
PRM	-	Probabilistic Roadmap
PSO	-	Particle Swarm Optimization
RAM	-	Random Access Memory
r_{min}	-	Minimum Turning Point
RRT	-	Rapidly Random-exploring Tree
s	-	Seconds
SA	-	Simulated Annealing
SDN	-	Software Define Networking
S_p	-	Starting Point
T_p	-	Target Point
v	-	Velocity
VD	-	Voronoi Diagram
VG	-	Visibility Graph
VRBVG	-	Virtual Rubber Band Visibility Graph
VWO	-	Variable Waypoint Offset
W_{IE}	-	Free-collision path inside equilateral space
w_s	-	Free-collision path
ρ	-	Input angle

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CHAPTER 1

INTRODUCTION

This chapter covers the project background, problem statement, objectives and scopes of projects.

1.1 Project background

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Finding a collision-free path in an assigned environment from a predefined starting point (S_P) to a target point (T_P) is one of the key preconditions for an autonomous vehicle [1]. This is called path planning, which is one of the vital elements of autonomous systems. Nowadays, research on autonomous vehicles has been growing rapidly mainly due to the availability of the enabling technologies such as LIDAR (Light Detection and Ranging), night vision camera and high speed microprocessor that can process data in a short amount of time. Among the purposes for an autonomous vehicle is to assist a tired driver, who drives for a long journey, to manoeuvre the vehicle safely. As such, path planning plays an important role to ensure that the path traversed by the autonomous vehicle is collision-free.

There are several famous companies like Audi, Google, Tesla, Mercedes-Benz, and BMW to name a few which involve in the development of autonomous cars [2]–[4]. Google has created a functional prototype of a self-driving car [2]. Furthermore, in 2015, Baidu and BMW have launched the first self-driving car on China road [3]. Tesla has also released a software comprising of self-driving feature for their customers in 2015 [2].

Research on path planning, especially for the discovery of an optimal path, has been a growing interest among researchers in recent years [5]. There are several methods that have been used for path planning such as Visibility Graph (VG), Cell Decomposition (CD), Potential Fields (PF), Probabilistic Roadmap (PRM), Voronoi Diagram (VD), Rapidly-Exploring Random Tree (RRT), Genetic Algorithm (GA), Ant Colony Optimisation (ACO), Simulated Annealing (SA) and Particle Swarm Optimization (PSO). Among the path planning criteria taken into account before developing a path planning method/algorithm are minimal path length, completeness of path planning and lower computation time [5]–[8].

Path planning can be performed using several available methods and each method has its own advantages and disadvantages. In Cell Decomposition (CD) method, firstly the configuration spaces (C-space) will be decomposed into cells. After that, a connectivity graph will be built and lastly the path from the starting point to the target point is determined. The main disadvantage of this method is that the resulting path may not be the shortest one if the size of the cells is relatively large. On the other hand, if the size is too small, it requires more computation time to find a path [9]–[12]. Rapidly-exploring Random Tree (RRT) is a path planning method that applies sampling based algorithm. By using the starting point as the foundation, a new branch will grow until it reaches target point. The drawback of RRT is that it is difficult to be applied in a narrow path [5]. Potential Field (PF) method uses attractive and repulsive forces for path planning. In a path planning for a vehicle, the target point acts as an attractive force to attract vehicle, and the obstacle acts as a repulsive forces to avoid the vehicle colliding with obstacle. The vehicle becomes the point under the influence of the field generated by PF. The problem of PF is the local minima will occur when zero potential field is generated which results in the path cannot be found for which the path planning is incomplete [13], [14]. On the other hand, path planning using Voronoi Diagram (VD) finds equidistant point from the nearest two or all the obstacles. In this technique the resulting path is not the optimal one which is undesirable [9], [14]. Genetic Algorithm (GA) uses a natural selection process to create a path planning. The drawback of GA is the solution may not be found in a narrow condition and thus local minima will occur. Besides that, the speed and accuracy of the algorithm decreases in a bigger environment of search spaces [7], [15]. Visibility Graph (VG) method uses a line to connect the mutually visible vertices (nodes) of each obstacle, the starting point, and the target point. This method is capable of producing

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a minimum length path and is complete [1], [2]. However, the computation time of VG increases when the number of obstacle is increased [3], which makes it not applicable in real time path planning. Considering the advantage of VG method which is able in finding an optimal path and is complete, in this research, an algorithm called Equilateral Spaces Oriented Visibility Graph (ESOVG) is proposed. ESOVG creates equilateral space based, in which a path planning will take place. However, ESOVG cannot guarantee that the planned path is collision free. Hence, ESOVG is modified to be iterative and is called Iterative Equilateral Space Oriented Visibility Graph (IESOVG). IESOVG will find a new path if the previous one is not collision-free until a safe path is found within the equilateral space by increasing the so-called input angle. IESOVG is able to generate an optimal path with significantly low computation time and is complete. The algorithm is implemented in a car-like robot.

On the other hand, the kinematic constraint is a factor in path planning that affects the result of path feasibility. Due to this, an autonomous vehicle is incapable of tracking the planned path faithfully. A planned path, which is normally piece-wise linear, typically consists of several sharp turns and this might result in the vehicle fails to track. There are several techniques that can be used to adjust a planned path to be feasible such as Bezier curve, Clothoid, and Dubin's curves to name a few. In this project, Bezier curve has been chosen because it is easy to develop with less complexity compared to Clothoid [16]. Besides Bezier curve, Proportional (P) and Proportional-Derivative (PD) controllers have also been implemented to address the kinematic constraint.

In a nutshell, this project proposes path planning algorithms based on VG method, which are called ESOVG and IESOVG. After planning a collision-free path with IESOVG, to tackle the kinematic constraint of car like robot, P-controller, PD-controller and Bezier Curve are implemented to ensure that the car could track the planned path faithfully.

1.2 Problem statement

There are a number of existing methods for path planning such as Cell Decomposition (CD), Voronoi Diagram (VD), Visibility Graph (VG), Potential Fields (PF), Rapidly-exploring Random Tree (RRT), and Genetic Algorithm (GA). VG is considered one of the promising methods because it could find an optimal, collision-free path and is

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complete. Despite all the advantages, VG has a major issue which is it relatively slow in finding an optimal, collision-free path in obstacle-rich environments and therefore could not be applied in real time path planning [4]–[6]. In a real-time application, a path planning with low computation time is desirable. Planning and re-planning a path with long computation time might cause the robot to collide or crash. For instance, an autonomous car is required to re-plan a path because of a pop-up obstacle or any situation that requires re-planning. Besides computation time, another drawback of VG is the planned path is piece-wise linear which consists of many sharp turns and it is difficult to be tracked by an autonomous car because of the kinematic constraints. The kinematic constraints limit the degree of freedom of an autonomous car. Due to this, it is challenging for an autonomous car to track a piece-wise linear path.

1.3 Aim and objectives

The aim of this research is to develop algorithms for a car-like robot based on the visibility graph (VG) method to produce a collision free path. Besides that, this research also applies several approaches to overcome the kinematic constraints of a car-like robot.

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The objectives of these projects are:

1. To develop a computationally efficient path planning algorithm based on VG for a car-like robot.

2. To implement P-Controller, PD-Controller and Bezier curve to overcome the kinematic constraint of a car-like robot.

3. To validate the performance of the developed algorithm.

1.4 Scopes of project

In the project, analysis regarding the computational time of the proposed algorithms and the conventional VG algorithm is carried out. The limitations of this project are:

1. The efficiency of the proposed algorithms and the conventional VG is tested using Matlab software run on a personal computer with 2.4 GHz processor and 4 GB RAM.
2. No hardware developed in this project and no experiment is conducted using hardware.
3. The C-space is applied to evaluate the IESOVG and conventional VG algorithm performances and it contains only randomly distributed rectangular-shaped static obstacles. The initial value tested to determine the optimal value of ρ is 10 ° until 50 °
4. The proposed algorithm is designed in two-dimensional (2-D) space.
5. The kinematic constraint considered in the developed algorithm is the minimum turning radius of the car-like robot.
6. To tackle the kinematic constraint of car-like robot, three approaches are used namely P-Controller, PD-Controller and Bezier curve. All approaches are applied to reduce the orientation and heading errors during the traversal of the car-like robot through a planned path.

1.5 Thesis structure

This thesis consists of five (5) chapters. Chapter 1 introduces the project with some background, problem statement, objectives, scope and structure of the thesis. Chapter 2 presents the literature review regarding the topic of the research including the introduction of path planning and its criteria, the explanation of visibility graphs, details of graph search algorithm and the description of car-like robot's kinematic constraints. Chapter 3 explains the methodology for the proposed algorithm. Chapter 4 presents the proposed algorithms and discusses the findings and approaches used. Lastly, Chapter 5 concludes this project and provides recommendation for future work.

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CHAPTER 2

LITERATURE REVIEW

This chapter discusses the previous related research of the project.

2.1 Introduction to path planning

There are several types of path planning for robots such as combinatorial, bio-inspired, rapidly-exploring random tree and potential field's algorithm. Each of them has its benefits and drawbacks in terms of the resulting path length, computation time and completeness. A method that can produce path with shortest length is desirable as this will highly reduce the energy consumed by a robot and saving cost and time to move from point A to point B [7]–[11]. Besides that, the computation time of path planning method is always a consideration in order to ensure that a collision-free path can be planned in a short duration time should the environment changes. A path planning algorithm with low computational time is important so that it can be used in real-time. Furthermore, it is highly required that a path planning method is complete, which means that a path could be planned if one exists [12] and gives the negative report if otherwise. The aforementioned three aspects, i.e., (i) produce shortest (optimal) path, (ii) low computation time and (iii) complete, are the criteria of path planning that are typically taken into account before designing a path planning algorithm. Table 2.1 shows several known conventional path planning algorithms that fulfil some or all the criteria. Visibility Graphs (VG) is a path planning method which is based on combinatorial planning. Combinatorial planning builds a path planning by solving queries along the way.

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VG advantages are it is able to solve path planning problem by finding the shortest distance without the possibilities local minima occur[5], [7], [13], [14] and it satisfies two criteria of optimal path planning, i.e. complete path planning and minimum path generated [7], [8], [13]. Besides that, VG is also easy to be implemented due to the simplification of equation [5]. The drawback of VG is its computation time increases when the number of obstacles in C-spaces is increased. C-space is applied so that the size of the autonomous car can be reduced to a point and the size of obstacle can be enlarged based on the size of autonomous car [15].

Table 2.1: Summary for path planning methods

Path planning properties	-	**Lower Computation Time**	**Completeness**	**Minimal Path Generated**
Combinatorial path planning	Visibility Graph (VG)	No. the computation time of VG increases when the number of obstacles increase.	Yes. VG is able to solve a path planning without the possibility of local minima occur.	Yes
	Voronoi Diagram	Yes	Yes	Minimum path unable to be generated
	Cell-Decomposition method	The computation time increases if the size of cells are small.	Yes	Minimum path hard to be generated if the size of the cells are too large.
Bio-inspired method	Genetic Algorithm (GA)	Yes. since GA is a meta-heuristic and parallel based algorithm.	Local minima might occur in narrow environments.	Not guaranteed.
	Simulated Annealing (SA)	Yes. Since SA is a meta-heuristic based algorithm.	Yes. The gradual probabilistic properties allow this algorithm to avoid local minima.	Hard to determine.
	Ant-Colony Algorithm (ACO)	Yes. Since ACO is a meta-heuristic based algorithm.	Local minima.	Cannot be determined because of the randomly picked path.

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Table 2.1: Summary for path planning methods (continued)

Rapidly-exploring Random Tree	-	The computation time will increase depends on the size of tree generate.	Yes.	No
Potential Fields	-	Yes	Local Minima might occur before reaches target point.	No

The Voronoi diagram (VD) has a tendency to augment the separation between the robot and obstacle in the search space. For every point in the free space, the separation to the closest obstacle is figured. VD using an equidistant point from two or all the nearest obstacle [16]. The advantages of the VD is the computation scale is small and the global optimal solution can be obtained [11] and a complete algorithm, it able to solve a path without the possibility of local minima occurred. However, the limitation of the VD is that it is incapable to produce the shortest path [13], thus there is a high wastage in energy consumption and cost.

Cell-decomposition (CD) method finds a cell that is not occupied by obstacles. The environment is divided into the cell which is discrete and non-overlapping. A finite graph is built by relegating every cell as a hub. Basically, there are two types of decomposition method, firstly by exact decomposition and secondly by approximation decomposition [10]. The advantage of CD is an assurance to find a collision-free path if one exists and attainable by the robot, thus CD is a complete algorithm since it can solve the path without the possibility of local minima occurred [17]. Nevertheless, the drawback of CD are (i) if the cell generated is too coarse, the minimum path length generated cannot be achieved and (ii) if the cell is too small, the longer computation time is needed [12], [16], [18]. The cell decomposition method also does not work really well in a dynamic environment and real-time path planning [17], [19], [20].

The bio-inspired method is inspired from nature. Genetic algorithm (GA) using an application of operators to emulate natural selection process. The disadvantage of GA is that there are possibilities that solution cannot be found in narrow environments, the local minima conditions might occur. On the other hand, GA is the algorithm worked in parallel, thus less computation time is used. GA is meta-heuristics so it does not guarantee the shortest path distance [21]–[23].

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