UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A MOTION PLANNING AND OBSTACLE AVOIDANCE ALGORITHM USING ADAPTIVE NEURO FUZZY INFERENCE SYSTEM FOR MOBILE ROBOT NAVIGATION

FARAH KAMIL ABID MUSLIM

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By

FARAH KAMIL ABID MUSLIM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

May 2017

DEDICATION

To the spirit of my respectful father who taught me the meaning of courage and always had confidence in me.

Farah Kamil Abid Muslim

May 2017

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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May 2017

Chairman : Associate Professor Tang Sai Hong, PhD
Faculty : Engineering

The autonomous navigation of robots is one of the most significant issues about robotics because of its difficulty and dynamism. This is because it relies on environmental situations such as the interface between themselves, individuals or any unexpected changes within the surroundings. It is necessary that the trajectory to the robots' destination be calculated online, and throughout motion, to enable the robot to respond to variations within the environment. However, the essential difficulty in solving this issue may obstruct a sufficiently quick solution from being calculated online, given sensible calculation resources. These come from high dimensions of the exploration of space, geometrical and kinematic features of the obstacles. Especially their velocities, uncertainty, cost function to be improved, and the robot's dynamic and kinematic model,

This research focuses on the existing drawbacks and inefficiencies of the available path planning approaches within unknown dynamic environments. These drawbacks can be categorized as the problem encountered in this research into four categories, including inability to plan under uncertainty of dynamic environments, non-optimality, failure in crowded complex situations, and predicting the obstacle velocity vector.

In this research, a new sensor-based online approach was proposed for generating a collision-free trajectory for differential-drive wheeled mobile robots, which could be applied to an unknown dynamic environment, in which the obstacles are moving and their speed profiles are not pre-identified. This approach depends on future predictive behaviour to predict the obstacles' future route and priority behaviour to make decisions about the best navigation to reach the destination safely. This approach

employs several intelligent techniques to improve the performance of the planner in terms of the quality of the resulted path, runtimes of the planner, ability to solve complex problems effectively and capability of planning in unknown dynamic environments.

Firstly, a new sensor-based online approach is planned to reach the first and second objective of the research. This comprises planning in unknown dynamic environments and predicting the obstacle's velocity vector in order to find safe and fast reactive trajectories. This is particularly true in unforeseen environments that contain both static and dynamic obstacles.

After this, the third objective of the research is planning in a crowded complex situation to evaluate the risk of collision between the robot and the obstacle's trajectory using a fuzzy logic controller. This would allow the FLC to generate a local path for an obstacle avoidance system unique to mobile robot navigation in dynamic environments.

Finally, the last objective is to improve the optimality of the new approach using a robust Machine Learning strategy. An adaptive neuro-fuzzy inference system (ANFIS) was designed which constructs and optimizes a fuzzy logic controller using a given dataset of input/output variables in order for the mobile robot to learn. This depends on the previous outcomes to generate a short path with a low runtime for an obstacle avoidance system unique to mobile robot navigation in dynamic environments.

The proposed multilayer decision approach successfully guides the robot in uncertain and ever-changing surroundings. It also efficiently predicts the obstacles' velocity vector. The designed multilayer decision-based fuzzy logic model effectively solves the path planning queries in crowded and complex situations without any failure. Finally, the proposed ANFIS generated FLC successfully improves the optimality and reduces runtime rates of the proposed FLC planner. The present algorithm exhibits attractive features such as high optimality, high stability, low running cost and zero failure rates. The failure rate were zero for all test problems. The average path length for all test environments is 16.51 with standard deviation of 0.49 which gives an average optimality rate of 89.79%. The average runtime is 4.74 (standard deviation is 0.26).

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN PERANCANGAN GERAKAN DAN ALGORITMA PENGELAKAN HALANGAN MENGGUNAKAN SISTEM PENYESUAIAN INFERENS NEURO UNTUK PENGEMUDIAN ROBOT BERGERAK

Oleh

FARAH KAMIL ABID MUSLIM

Mei 2017

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Pengemudian berautonomi robot adalah salah satu isu yang paling penting tentang robotik kerana kesukaran dan dinamismenya. Ini kerana ia bergantung kepada keadaan persekitaran seperti antara muka di antara mereka, individu atau mana-mana perubahan yang tidak dijangka di sekitarnya. Adalah perlu agar trajektori ke destinasi robot itu dikira dalam talian, dan sepanjang gerakan, bagi membolehkan robot tersebut bertindak balas kepada perubahan di persekitaran. Walau bagaimanapun, kesukaran yang penting dalam menyelesaikan isu ini, yang datang dari dimensi tinggi ruang penerokaan, ciri-ciri geometri dan kinematik halangan terutama sekali halaju mereka, ketidakpastian, fungsi kos yang perlu diperbaiki, serta model dinamik dan kinematik robot itu, boleh menghalang penyelesaian yang cepat dikira dalam talian, memandangkan sumber-sumber pengiraan yang wajar.

Kajian ini memberi tumpuan kepada kelemahan dan ketidakcekapan pendekatan perancangan laluan yang sedia ada di dalam persekitaran dinamik yang tidak diketahui. Kelemahan-kelemahan ini boleh dikategorikan sebagai masalah yang dihadapi dalam kajian ini terbahagi kepada empat kategori termasuk ketidakupayaan merancang di bawah ketidaktentuan persekitaran yang dinamik, bukan-optimum, kegagalan di dalam keadaan kompleks sesak, dan meramal vektor halaju halangan.

Dalam kajian ini, pendekatan baru dalam talian berasaskan-sensor telah dicadangkan untuk menjana trajektori tanpa-perlanggaran untuk robot bergerak beroda pacuan-kebezaan yang boleh digunakan untuk persekitaran dinamik yang tidak diketahui, di mana halangan-halangan bergerak dan profil kelajuan mereka tidak di kenal pasti sebelumnya. Pendekatan ini bergantung kepada tingkah laku ramalan masa depan untuk meramalkan laluan dan tingkah laku keutamaan halangan untuk

membuat keputusan mengenai pengemudian yang terbaik untuk sampai ke destinasi dengan selamat. Pendekatan ini menggunakan beberapa teknik pintar untuk meningkatkan prestasi perancang dari segi kualiti laluan yang terhasil, masa larian perancang, keupayaan menyelesaikan masalah yang kompleks dengan berkesan dan keupayaan perancangan di dalam persekitaran dinamik yang tidak diketahui.

Pertama, suatu pendekatan baru dalam talian berasaskan-sensor dirancang untuk mencapai objektif-objektif pertama dan kedua kajian yang terdiri dari perancangan di dalam persekitaran dinamik yang tidak diketahui dan meramalkan vektor halaju halangan untuk mencari trajektori reaktif yang selamat dan cepat di dalam persekitaran yang tidak diduga yang mengandungi kedua-duanya halangan statik dan dinamik.

Kemudiannya, objektif ketiga kajian ini ialah merancang di dalam keadaan kompleks yang sesak untuk menilai risiko perlanggaran antara robot dan trajektori halangan menggunakan pengawal logik kabur (FLC) untuk menjana perhampiran dengan laluan untuk suatu sistem mengelakkan halangan untuk pengemudian robot bergerak di dalam persekitaran dinamik.

Akhir sekali, objektif terakhir iaitu untuk meningkatkan sifat optimum pendekatan baru menggunakan strategi Pembelajaran Mesin yang teguh. Suatu sistem penyesuaian inferens neuro-kabur (ANFIS) direka yang membina dan mengoptimumkan pengawal logik kabur menggunakan set data pembolehubah input/output yang diberi. Untuk pembelajaran robot bergerak itu bergantung kepada hasil sebelumnya untuk menjanakan jalan singkat dengan masa larian rendah untuk sesuatu sistem pengelakan halangan bagi pengemudian robot bergerak di dalam persekitaran dinamik.

Multilayer pendekatan keputusan yang dicadangkan telah berjaya membimbing robot dalam persekitaran yang tidak menentu dan sentiasa berubah-ubah. Ia juga cekap meramalkan vektor halaju halangan. Model logik kabur berasaskan keputusan direka multilayer berkesan menyelesaikan jalan yang merancang pertanyaan dalam keadaan yang sesak dan kompleks tanpa sebarang kegagalan. Akhir sekali, ANFIS cadangan dijana FLC berjaya meningkatkan optimaliti dan mengurangkan kadar runtime daripada FLC perancang yang dicadangkan. Kadar kegagalan adalah sifar untuk semua masalah ujian. Purata panjang jalan untuk semua persekitaran ujian adalah 16.51 dengan sisihan piawai 0.49 yang memberikan kadar optimaliti purata 89.79%. The runtime Purata 4.74 (sisihan piawai ialah 0.26).

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of Supervisory committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3-D	Three Dimensional
ACO	Ant Colony Optimization
AICO	Approximate Inference Control Method
ANFIS	adaptive Neuro-Fuzzy Inference System
ANN	Artificial Neural Network
APF	Artificial Potential Field
AUV	Autonomous Underwater Vehicle
BEA	Bacterial Evolutionary Procedure
CCPP	Complete Coverage Path Planning
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CVM	Curvature Velocity Method
d	Euclidean Distance
DC	Directive Circle
DForC	Dynamic Force Field Controller
DP	Desired Path
DPPA	Dynamic Path Planning Algorithm
DW	Dynamic Window
EA	Escaping Algorithm
FD	Front dynamic
FS	Front Static
FLC	Fuzzy Logic Controller
H	High
HBMO	Honey Bee Mating Optimization
IP	Intersection Points
GA	Genetic Algorithm
GPS	Global Positioning System
L	Low

L	Total Length
LD	Left Dynamic
LS	Left Static
MLD	Multilayer Decision
MRS	Multi-Robot System
N	Normal
NMPC	Non-linear Model Predictive Control
n	Number of Points Along the Path
O (t)	The Location of Obstacle at *t* Period
OP	Operator
PRM	Probabilistic Roadmaps
PSO	Particle Swarm Optimization
q_j	Range Quarters
RBB	Randomized Bridge Builder
RD	Right Dynamic
RHC	Receding Horizon Control
R_i	Sensor Layers
ROS	Robot Operating System
RRT	Rapidly Exploring Random Trees
RS	Right Static
r (t)	The Location of Robot at *t* Period
SA	Simulated Annealing
SIPP	Safe Interval Path Planning
Std	Standard Deviation
$\check{T}$	Sample Time
t	Time
VD	Vision Domain
VF	Very Far
VFH*TDT	Vector Field Histogram with Time Dependent Tree
VFH	Vector field Histogram
VO	Velocity Obstacle Approach
VH	Very High
VL	Very Low

v	Translational Velocity of the Robot
ω	Angular Velocity of the Robot
WMR	Wheeled Mobile Robot
φ	Steering Direction

CHAPTER 1

INTRODUCTION

In this chapter, the background of the study is being mentioned with supplement information regarding the present inefficiencies of motion planning algorithms. Then, the research problems are going to be expressed. Afterward, the objective of the research will be introduced in relation to the stated problems. Next, the scope of this study will be identified with supporting details about the robot and its environments. Finally, the organization of the thesis will be outlined.

1.1 Background of the study

Robots are currently replacing humans in different activities in various sectors, which vary from typical robots for industrial applications to self-directed robots for difficult tasks, for instance space exploration (Gasparetto et al., 2015). Robotic motion planning is a promising area of study in the field of robotics (Shih et al., 2013). Robot path planning is to create a collision-free route from a starting point to a goal point in an environment while .achieving the shortest collision free route and low run time (Abbadi & Přenosil, 2015).

Based on the data acquired from the environment, there are two types of motion planning approaches, namely offline path planning and online path planning (Xue & Xu, 2011). As the names suggest, offline path planning is a global optimization approach while online path planning performs only a local optimization. Offline algorithms require an obstacle map of the robots' environment. The path is pre-calculated and then given to the robot to execute. While online path planning is used to avoid obstacles by reacting to data collected from on-board sensors. It may be used when a map of the mobile robots' environment is not known or, if an unexpected obstacle was encountered during the execution of a pre-computed path (Pasha, 2003).

Path planning can be widely categorized in two main methods: classical and heuristic. The classic approaches suffer from numerous disadvantages, such as a high time complication in high dimensions, and catching in local minima, which render them ineffective in practice (Masehian & Sedighizadeh, 2007). Consequently, the application of the heuristic approaches was extended due to their achievement in addressing problems such as computational complexity, exploration and local minima (Tang et al., 2012).

Path planning in static environments is a thoroughly studied problem that can typically be solved very efficiently. However, planning in the presence of dynamic obstacles is still computationally challenging because it requires adding time as an additional dimension to the search-space explored by the planner (Phillips & Likhachev, 2011).

The traditional mobile robot planning approaches are not robust enough and unable to overcome the challenges. These challenges are the dynamic environment and the insufficient information available on the environment. As a result, many reactive approaches were introduced allowing the use of artificial intelligence techniques, where problem solving, learning and reasoning are the main issues (Faisal et al., 2013).

Over the course of the last few decades, there has been an extensive amount of effort on enhancing path planning algorithms in dynamic environments and in diverse extensions with proven advantages. Each resulted algorithm goes on to overcome one of the existing inefficiencies as follows:

1. Inability to plan under uncertainty of dynamic environments: Conventionally, global planners rely on a complete map of the environment in order to calculate the ideal and collision-free path between the starting point and the ending point prior to execution of the robot. The original plans of those conventional algorithms must be revised accordingly if a dynamic environment is encountered (Dijkstra, 1959; Hart et al., 1968). In practise, environment of robots often includes various hazard sources that robots must avoid, for example landmines, fire in rescue duty, and war enemies. Since it is impossible or expensive to acquire their accurate locations, decision-makers know only their action ranges in most cases (Zhang et al., 2013). Mobile robots must be able to evade both static and moving obstacles (Ferguson et al., 2006). Algorithms such as sampling-based methods (Khaksar et al., 2012) are not suitable for online planning when involving moving obstacles, due to the fact that these methods are designed based on a static environment model. These models are time-consuming when applied to a dynamic environment (involving interpolation cycle during each update, see (Huptych & Röck, 2015)). Therefore, classical path planning methods such as Visibility Graph (Lozano-Perez, 1987), Voronoi Diagrams (Leven & Sharir, 1987), Grids (Weigl et al., 1993), Cell Decomposition (Regli, 2007), Artificial Potential Field (Khatib, 1985), Rule Based methods (Fujimura, 1991) and Rules Learning techniques (Ibrahim & Fernandes, 2004) are not practical (Mohanty & Parhi, 2013). Occasionally, these algorithms are optimized to handle a specific problem at the expense of sacrificing the performance of other parameters such as increasing of the computational cost of the algorithm.

2. The problem of optimality: In most applications the focus is on obtaining the shortest path in order to decrease the collision probability and hasten the navigation process. Nevertheless, it is very challenging to compute the optimal motion plans (Zhao et al., 2016). Resolution-optimal solution paths for problems involving low-dimensional spaces can be determined via grid-based methods (e.g. A* or D*) (Stentz, 1997). Subjected to a specific quality criterion, the optimal path can be determined implicitly via some deterministic path planners such as the visibility diagram and the Voronoi Diagram (Latombe, 1990). Nevertheless, such methods are limited to low-dimensional spaces and only deal with polygonal obstacles. Sampling-based algorithms, such as RRT, are attractive because they can be used to solve complex high-dimensional problems. However, the solution quality may be affected if these algorithms are not optimized (Devaurs et al., 2016). Advanced versions of these

algorithms have been proposed. However, they are inefficient in handling moving obstacles.

3. Failure in crowded complex situations: Classic algorithms have been tested on some specific environments and it has been found that they are unable to find a feasible solution within a reasonable time frame. Results involving local minima may be obtained (Wang et al., 2007). It is noted that the execution and the safety requirements for the planned paths of non-holonomic robots are more rigorous in difficult and crowded situations (Liu et al., 2013). Although various improved versions of robot navigation algorithms have been proposed (Khaksar et al., 2014; Kuffner & LaValle, 1999), most of them are problem-specific and they perform poorly in dangerous situations (i.e. robot is surrounded by moving objects).

4. The problem of predicting the obstacle velocity vector: Some algorithms focus on handling dynamic and uncertain environments (Ali et al., 2013; Faisal, Hedjar et al., 2013; Stentz, 1995), in which the alteration of the environment came from the absence of obstacles or the presence of unexpected obstacles by relying on the sensor of the robot. Therefore, obstacles in these environments are not purely dynamic in terms of speed and moving vectors (i.e. unpredicted motion). Several improved algorithms have been proposed to circumvent this issue (Chinag & Ding, 2014); however, the parameter such as optimality has inevitably been reduced.

1.2 Problem Statement

This study focuses on the present drawbacks and inefficiencies of the available motion planning approaches in dynamic environments. These drawbacks can be classified as the problems encountered in this study as follows:

The problem of planning under the uncertainty of dynamic environments: Because the whole information of a dynamic environment will alter along with the motion of obstacles, and also because the hazard sources such as landmines have uncertain locations, the difficulty and uncertainty of the motion planning problems rise significantly in dynamic environments (Miao, 2009; Zhang et al., 2013) . If a planner takes too long to return a new path, then a collision can occur with a moving obstacle (Phillips & Likhachev, 2011). Some algorithms are optimized to handle this specific problem at the expense of sacrificing the performance of other parameters such as increasing of the computational cost of the algorithm.

The problem of predicting the obstacle velocity vector: The most important factor which has a strong effect in dynamic motion planning is the relative velocity. It is defined as the relative velocity vector of an adjacent obstacles movement in a forward trajectory with regard to the robot. In the approaches mentioned, the authors did not explicitly use this factor as a constraint (Dongshu et al., 2011). The problem happens when the robot and obstacle move at the same velocity and direction, so the robot cannot pass the obstacle and never reaches the goal unless it predicts the velocity vector of the obstacle and changes the direction as shown in Figure 1.1.

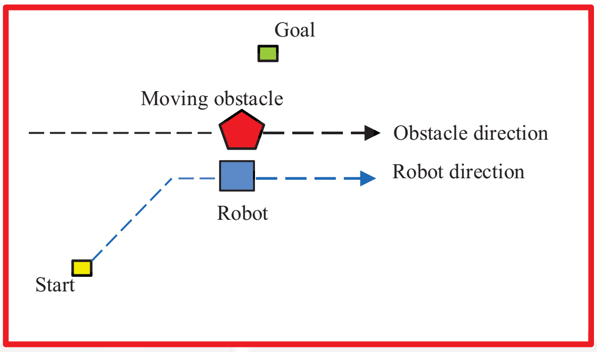

Figure 1.1: Significant issue in a dynamic environment

The problem of planning in crowded complex situations: Traditional path planning methods also are not suitable for planning paths in dynamic environments because of their lack of adaptively and robustness. It worked efficiently in complicated environments with arbitrarily shaped obstacles; however, it can only deal with the static environments (Li et al., 2012; Mingxin et al., 2010). On the other hand, heuristic algorithms try to find a better path in a short time but do not always guarantee to find a solution (Masehian & Sedighizadeh, 2007; Weerakoon et al., 2015). There is no algorithm which can perform efficiently in crowded dynamic environments especially when the robot is stuck inside a dangerous situation. The problem happens when the robot decides to move inside a dangerous area where three moving obstacles are moving toward each other and will collide with this next position. The robot cannot chose how to escape from them because the robot has a different solution for each moving obstacle, for instance the decision about the obstacle that is moving towards the right direction is to move left and is different from the decisions about two other obstacles which are moving left and down. Therefore, a collision will happen unless it is able to predict the dangerous area and change its next position to another position, which has a lower risk of collision and unobstructed direction as shown in Figure 1.2.

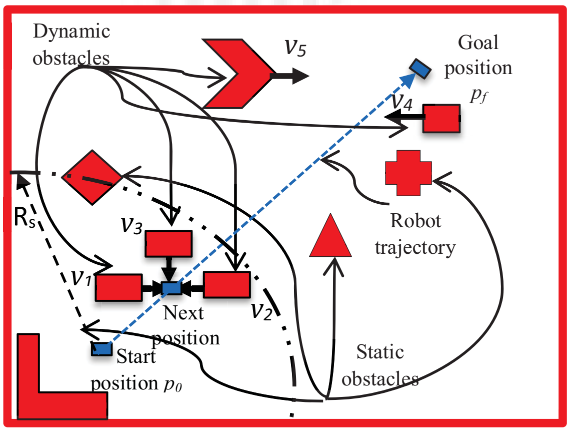

Figure 1.2 : Significant issue in a dangerous situation

The problem of optimality: the available path planning algorithms generate high-cost solutions with path lengths far from the optimum available solutions because these approaches focus on how to avoid obstacles and neglect other parameters such as optimality. This in turn makes them inappropriate for rapid dynamic movement (Faisal et al., 2013). The optimality problem has been studied and improved by many researchers but these are not suitable for planning paths in crowded dynamic environments (Li et al., 2016).

The above mentioned problems can be summarized as follows: the problem of planning under the uncertainty of dynamic environments, the problem of predicting the obstacle velocity vector, the problem of planning in crowded complex situations and the problem of optimality. Some of these problems have been studied and improved by many researchers but there is no work about combining all of them together.

1.3 Objective of the Study

The overall aim of this research is to navigate a mobile robot from its' starting position to destination in an unknown dynamic environment. Therefore the following objectives have to be met respectively to fulfil the overall aim of the research.

(1) To develop a new approach to avoid static and dynamic obstacles in planning the path of a mobile robot in unknown dynamic environments, to find a safe path and to react quickly.
(2) To integrate a decision making process with predictive behaviour of the obstacle's velocity vector by using a new idea of the robot's sensory system information.
(3) To plan in crowded complex situations to evaluate the risk of collision between the robot and the obstacle's trajectory to find a smooth path.
(4) To improve the efficiency of the new approach using a robust Machine Learning strategy by teaching the mobile robot depends on the previous outcomes to generate a short path with low runtime for an obstacle avoidance system in unknown dynamic environments.

1.4 Scope of the Study

In this section, the characteristic of the environments and the robot will be described in detail. Then, the author will introduce the performance appraisal methods that have been used for comparing the proposed algorithm with other considered path planning methods.

The environment is represented as a 2D space and filled with a limited number of static obstacles, in addition to dynamic obstacles which have different shapes. The obstacles move with different and continuous linear velocities and the positions of obstacles are ever-changing in every run.

The environment is unidentified for the planner before the planning and the only obtainable information is the coordination of the beginning and the end position which are static. The mobile robot is considered to have two degrees of freedom, and is also considered to be a Wheeled Mobile Robot (WMR), which has square shape centred at (r_x, r_y). It also has two autonomously-driven rear wheels and a castor front wheel, as represented in Figure 1.3. The configuration of a square robot at time *t* is displayed by $r_c(t) = (r_x(t), r_y(t), r_\varphi(t))$, the first two of which specify the coordinates of the centre of the robot around which it rotates (Source), and $r_\varphi(t)$ displays the robots orientation measured by its angle in relation to the positive x-axis.

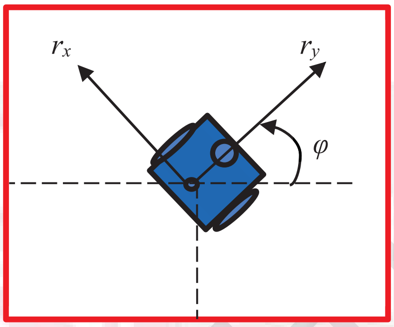

Figure 1.3 : The configuration of a square robot

The kinematic model of the *WMR* with two autonomously driven rear wheels and a castor front wheel is formulated as:

$$\dot{k} = f(k, n) = G(k)n \tag{1.1}$$

Where $k=[x, y, \varphi]^T$ is the state vector, $n= [v, \omega]^T$ is the input vector, and that

$$G(k) = \begin{bmatrix} \cos\varphi & 0 \\ \sin\varphi & 0 \\ 0 & 1 \end{bmatrix}$$

Equivalently, this can be formulated as

$$\dot{x} = v\cos\varphi \tag{1.2}$$

$$\dot{y} = v\sin\varphi \tag{1.3}$$

$$\dot{\varphi} = \omega \tag{1.4}$$

$$\dot{x} = \frac{1}{2}(v_r + v_l)\cos\varphi \tag{1.5}$$

$$\dot{y} = \frac{1}{2}(v_r + v_l)\sin\varphi \tag{1.6}$$

$$\dot{\varphi} = \frac{1}{l}(v_r - v_l) \tag{1.7}$$

In the proposed case, to achieve a straight line trajectory, it is assumed that:

$v_l\ (t) = v_r\ (t)$

$v_r\ (t) = v_l\ (t) = v\ (t)$

$\omega\ (t) = \dot{\varphi}(t) = 0$

At this point, the state vector $k=[x,\ y,\ \varphi]^T$ indicates the generalized location (position and direction) of the robot with relation to a stable reference axis, and the control vector $n= [v,\ \omega]^T$ indicates the linear and angular velocities of the robot.

It is also supposed that the robot wheels do not slip, and this is stated by the nonholonomic restriction.

$$\dot{x} \sin\varphi - \dot{y} \cos\varphi \quad (1.8)$$

The obstacles are characterized by arbitrary shapes. The velocity of an obstacle is (v_x, v_y), where the components on x and y axes are indicated by subscripts x and y respectively. Obstacles may be stationary or dynamic and their speed set randomly (The velocity of obstacles are equal to or less than the velocity of robots). Obstacles location and their velocity vector (speed and orientation) are unidentified to the robot. It is presumed that the obstacles are recognizable by the robot and move along arbitrary trajectories.

Since the speed and location of the obstacles are unidentified for the robot, it must be prepared with detectors or range sensors to obtain essential information. The robot has been prepared with range sensors with 360 degree finite direction that gets information from its surroundings. Its' detecting range is a circle centred at (x, y) with radius R_s**,** through which it makes a visibility scan and senses obstacle positions. When the robot arrives at a new position in the configuration space, it first calculates its distance to neighbouring obstacles' through its radial sensor readings, and then stores the outcome in a visibility matrix which is comprised of the position of visible obstacle points. Next, the obstacles' velocities are discovered as the robot calculates the obstacles' positions in two sequential repetitions (time intervals) to estimate each obstacle's speed vector.

The proposed method has been simulated in MATLAB 2013a programming environment for simulation and comparison studies.

In the beginning, the proposed method needs to be simulated in several test environments. 20 different arbitrary unknown dynamic environments including static and dynamic obstacles have been designed in 5 categories. These comprise convex, concave, maze, narrow passage and mix environments with 4 test environments in each category. Arbitrary environment means that the environment (positions of static and dynamic obstacles) for each run is different, as is the velocity of each obstacle. These environments have been designed cautiously to handle a variety of diverse possible situations. Descriptions and features of the test environments are offered in chapter 3.

Two procedures have been employed in this study to assess the performance of the proposed algorithm. The first procedure is to compare the length of the produced path by the proposed algorithm with the optimal path length generated from the visibility graph method. The visibility graph method builds a graph in which its nodes are the peaks of the obstacles and the start and destination positions. The generated graph is used to find the shortest path from the start point and the destination (Asano et al., 1985). It has been evidenced that the visibility graph gives an optimum solution.

After simulation studies and comparison with optimum solutions, the outcomes of the developed algorithms will be compared with a set of well-known path planning algorithms. These include Vector field histogram (VFH), Dynamic Window (DW), Bug Algorithm, PRM, RBB, Gaussian, and RRT. The selected algorithms have been carefully chosen to handle sensor-based behaviour of the proposed planners. These algorithms have been simulated in the MATLAB programming environment.

1.5 Thesis Outline

In this study, the problem of navigating a mobile robot in an unknown dynamic environment filled by a set of different shapes of static and dynamic obstacles has been studied. A novel sensor-based online planner is suggested which employs diverse intelligent components to enhance the performance of the planner. The author has designed a simulation framework in MATLAB which is used for analysing the performance of the algorithm. Moreover, diverse types of situations have been designed to determine the strength and advantage of the suggested planner in relation to the selected existing methods. Diverse evaluation criteria are used to support the analyses. The rest of this thesis is organised as follows:

Chapter 1 offers a detailed study on the current works in the field of motion planning regarding the problem of planning in an unknown dynamic environment.

Chapter 2 describes the research methodology in detail. Different heuristic and intelligent methods, which are used in the study to reach the research objectives, will be clearly specified.

Chapter 3 presents the outcomes of the study. A detailed discussion about the proposed algorithms, performance analyses and comparison outcomes will be provided with supplemental charts, graphs and tables.

Chapter 4 concludes the outcomes of the study with additional graphs and discussions. After that, the contribution of the research will be outlined and recommendations for further studies in this zone are given.

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