A Hybrid Obstacle Avoidance Method: Follow the gap with dynamic window approach

Aykut Özdemir
Mechatronics Education and Research Center
Istanbul Technical University
Istanbul, TURKEY
Email: ozdemirayk@itu.edu.tr

Volkan Sezer
Mechatronics Education and Research Center
Istanbul Technical University
Istanbul, TURKEY
Email: sezerv@itu.edu.tr

***Abstract*—Follow the Gap Method (FGM) is an obstacle avoidance method which uses gap arrays. This method recursively directs robot to the goal state while avoiding the obstacles through the safest gap. Since FGM is a geometric method, it does not consider the robot dynamics. For this reason, oscillations or collisions due to robot dynamics is possible. On the other hand, FGM calculates a desired heading angle but it does not give linear and angular velocity reference. Dynamic Window Approach (DWA) is one of the most popular obstacle avoidance algorithm which does take robot dynamics into consideration. It calculates best angular and linear velocity pair which is chosen by an objective function. In this paper, a FGM-DW approach which uses the strongest elements of FGM and DWA methods to achieve safe, smooth and fast navigation is proposed. The FGM-DW approach provides these concerns and meets the low level angular and rotational velocity requirement of FGM.**

I. Introduction

Motion planning techniques are designed to find geometrically admissible trajectory pairs connecting the robot initial position and the goal location without collisions. These methods can be divided into two major parts: global and reactive motion planning.

Global motion planning methods use priori information of obstacles and generate trajectories between the initial position and the goal position inside collision free space. This type of methods assume that the obstacles are static and the map is not updated by means of the sensory information. Probabilistic road maps (PRMs) [1], rapidly-exploring random trees (RRTs) [2], potential field methods [3], and cell decomposition based methods [4] belong in this category. These methods are problematic if the information of obstacles are inaccurate or not available. Moreover their execution time increases exponentially as a consequence of model and world complexities.

If the environment model and robot motion are uncertain; consequently any global motion plan becomes unrealistic from the standpoint of obstacle avoidance. Reactive motion planning methods focus on changing robot manoeuvres using the sensory information and goal position. These methods recursively detect obstacles and avoid them while driving the robot toward the goal point. Their key advantage over global planners is low computational complexity since these methods use only a small portion of the information about the environment. Reactive motion planning methods can further be divided into two types in accordance with their final output.

The first type of reactive motion planning methods are called directional approaches, which compute the appropriate robot heading angle for obstacle free navigation. Artificial Potential Field (APF) [3], Vector Field Histogram (VFH) [5], VFH+ [6], Nearness Diagram (ND) [7], Obstacle Restriction Method (ORM) [8] and Follow the Gap Method (FGM) [9] are the popular methods in this category. Potential field and vector field methods use repulsive and attractive forces which are generated by obstacles and goal point respectively. The ORM uses repulsive angle sets and sub-goals, whereas the ND and FGM methods use gap arrays located between the obstacles to determine the appropriate heading angle. Although these approaches efficiently generate the direction outputs, they are not sufficient for taking the robot dynamics into account.

Unlike directional approaches, velocity space approaches use dynamic properties of robots in order to perform obstacle free navigation. These methods presume that the robot travels along arcs. For instance the Curvature Velocity Method (CVM) [10] calculates possible curvatures by eliminating ones which collide with the obstacles. After pruning the redundant curvatures, the most appropriate velocity pair is calculated by a CVM's objective function. The Velocity Obstacles method (VO) [11] uses dynamic objects velocities in its workspace. These velocity values restrict the robot's actual velocity space. Consequently, the final velocity vector is selected among admissible velocities due to convergence measure to goal point. The Dynamic Window Approach (DWA) [12], [13] considers reachable velocities within a short time interval, named as admissible velocities. This method eliminates velocity pairs which are not able to stop the robot without collision. The remaining velocity pairs evaluated by the objective function and the velocity pair which has the maximum value is executed by this method.

In this paper, we propose a novel hybrid obstacle avoidance approach named as FGM-DW which combines the strongest elements of both FGM and DWA. This method retrieves the final heading angle from FGM method, and subsequently uses admissible velocity set calculation stage used as in the original DWA method. Finally, the most appropriate control signal is calculated from its new objective function. The proposed FGM-DW method directs the robot to safer regions with admissible angular and rotational speed pairs which are

978-1-5090-6724-4/17 $31.00 © 2017 IEEE
DOI 10.1109/IRC.2017.25

calculated by considering the robot dynamics.

The rest of paper organized as follows. Section II introduces the FGM. Section III introduces the original DWA method. Section IV explains the operating principle of the new FGM-DW method. Simulation results are presented in section V. Section VI concludes the paper.

II. Follow the Gap Method

The FGM uses the largest gap center angle, the goal angle and the minimum distance to obstacles for avoiding from collisions and it was found to be the most effective avoidance technique in a survey by Zohaib et al. [14]. This method calculates the guide heading angle with respect to a safety coefficient. The FGM steps are given as follows: In the first step, obstacles are enlarged by robot radius to obtain collision free space. In this space, the robot is assumed as a point robot. In the second step, this method finds the gaps from the polar obstacle distance histogram. For a circle shaped robot, the workspace and obtained polar obstacle distance histograms are demonstrated in Fig. 1 and Fig. 2 respectively. These demonstrations resemble the histogram grid representation and polar obstacle density used in the VFH method.

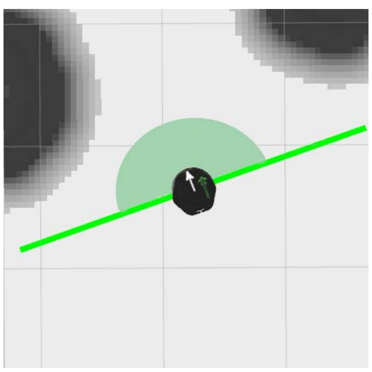


Fig. 1: Robot free space in the scene is represented in light and dark gray areas, black areas indicate enlarged obstacles. White arrow and light green arc indicate robot orientation and scan range, respectively.

In the final step, the FGM calculates gap widths from the polar obstacle distance histogram. Then it measures angle difference between center point of the largest gap and the robot orientation. The minimum distance to obstacles, goal angle and largest gap center angle are used in Eq. (1) to obtain guide heading angle. Detailed information about the calculation of the largest gap angle θ_{gap} which is the angle to the center of the safest gap, can be found in [9].

$$\theta_{guide} = \frac{\frac{\alpha}{d_{min}}\theta_{gap} + \theta_{goal}}{\frac{\alpha}{d_{min}} + 1} \tag{1}$$

The FGM calculates the guide heading angle between the goal angle and the gap center angle depending on its α parameter and the distance to the nearest obstacle value d_{min}. The relations between these variables are illustrated in Fig. 3 to give a better insight.

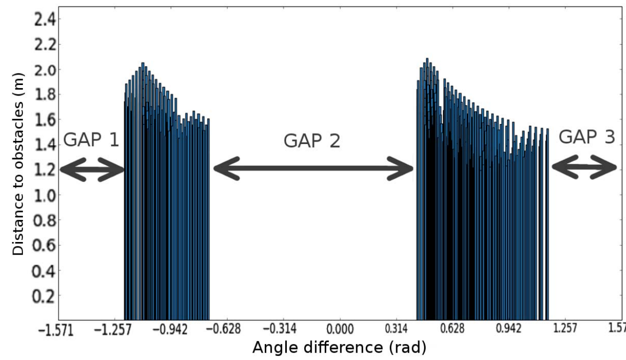


Fig. 2: Polar obstacle distance histogram. These distances are used to find gaps.

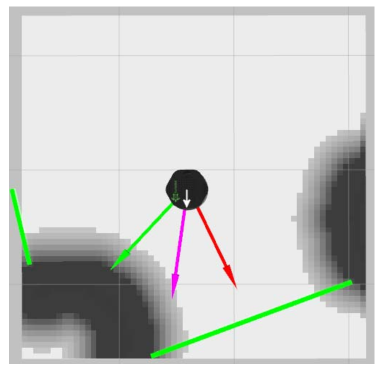


Fig. 3: White and green arrow indicate robot heading angle and goal heading angle, respectively. The maximum gap angle is highlighted in a red arrow, guide angle is shown as a purple arrow.

III. Dynamic Window Approach

The Dynamic Window Approach is a velocity space search method which takes robot dynamics into consideration. This method is a three stage process.

The first stage eliminates unreachable velocities coming from the acceleration limits of the robot. In the second stage, all velocity pairs which are not able to stop before colliding with obstacles are eliminated. In the third stage, DWA evaluates an admissible velocity set by maximizing its objective function shown in Eq. (2). DWA predicts the results of each velocity pair candidates in terms of final heading angle, minimum distance to obstacles and linear velocity values and chooses the optimum velocity pair by maximizing the objective function.

$$G(V,w) = \sigma[\alpha head(V,w) + \beta dist(V,w) + \gamma vel(V,w)] \tag{2}$$

The heading function $head(V,w)$ represents the approximation to goal angle and its value increases when the robot's heading approaches to target location. The aim of the distance function $dist(V,w)$ is to promote safe navigation. It calculates the minimum distance values to obstacles on the trajectory obtained from velocity pair. The velocity function $vel(V,w)$ calculates the linear velocity values in the velocity set. Coefficients α, β and γ are weights of these functions and σ is a smoothing operator. Maximizing this objective function results in safe trajectories to reach target as fast as possible. Possible outputs of a DWA implementation are illustrated in Fig. 4.

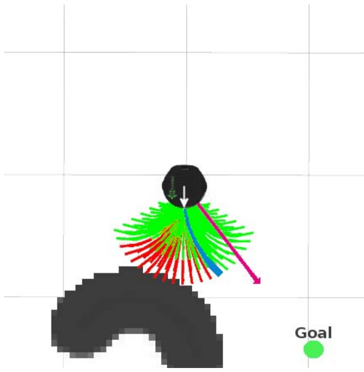


Fig. 4: Green and red trajectories indicate admissible trajectories and inadmissible trajectories, respectively. Goal heading angle is shown as the magenta arrow and best trajectory is the blue trajectory.

IV. FGM-DW Approach

Briefly, DWA recursively selects faster, safer and more goal oriented signals from the velocity space of the robot. This method has some drawbacks (e.g. local minima, considering only forward motions). On the other hand, the safety part of the FGM is very powerful since it's aim is to direct the robot into the center of maximum gap as much as possible. One of the main drawbacks of the FGM is it only calculates a desired heading angle and there is no calculation about robot velocity. For this reason, the FGM sometimes fails in narrow spaces when operating at high speeds. It also suffers from oscillations at high speeds and these oscillations may cause collisions (Case-1) or the problem of miss the goal region (Case-2). These cases are simulated in ROS Gazebo real world environment [15], [16] and demonstrated in Fig. 5. These results observed for the same parameters of FGM (0.5m/s linear speed and $\alpha = 1.0$).

As it is explained previously, FGM directs the robot to gap regions; however its oscillations cause further collisions especially when the robot's sensor range is limited. DWA is able to solve these problems with its adaptive velocity selection and early collision estimation features.

The combined FGM-DW approach is a three stage process and these processes are explained in following three subsections. Calculation of the guide angle with the FGM method is explained in the first subsection. In the second subsection, admissible velocity set calculation is touched on. Lastly, the objective function and final velocity pair calculation is explained in detail.

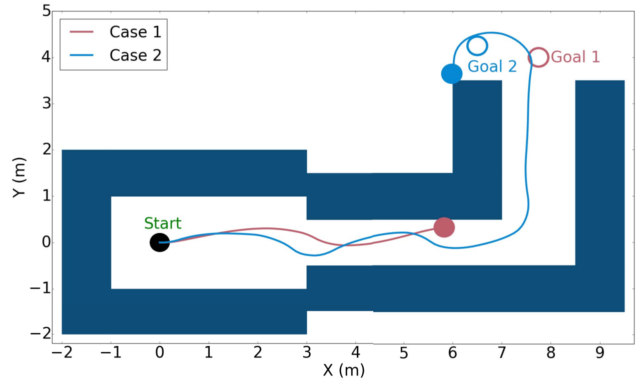


Fig. 5: FGM with proportional angle controller at 0.5m/s constant linear speed results in a cluttered environment.

A. Calculation guide angle with FGM

The guide angle is a composition of goal angle and gap angle and it gradually directs the robot to the goal position. As mentioned in Section II, guide angle can be derived from Eq. (1). It has been also pointed out that in this equation α and d_{min} values determine the guide angle approximation to the maximum gap angle.d_{min} is robot's distance from nearest obstacle. If the robot is close to the obstacles, d_{min} approaches to zero which means the robot is directed mostly to the safest gap center, otherwise it is oriented mostly to the goal.

B. Calculating admissible velocities

As mentioned before, DWA uses linear and angular accelerations $(\dot{V}, \dot{w})$ to calculate reachable velocities from current velocities (V_n, w_n) within a short time interval (t). The calculation of reachable velocities (V_r) is shown in Eq. (3).

$$V_r = \{(V,w) | V \in [V_n - \dot{V}t, V_n + \dot{V}t] \wedge \\ w \in [w_n - \dot{w}t, w_n + \dot{w}t]\} \quad (3)$$

Admissible velocities are reachable velocity pairs which are able to stop the robot before the collision. Calculation of these pairs depends on decelerations $(\dot{V}_{break}, \dot{w}_{break})$ of the robot and minimum distance between obstacles and trajectory generated with the velocity pair $(min_d(V,w))$. Admissible velocities (V_a) calculation is shown in Eq. (4). This equation comes from decelerated object's displacement calculation. In the original paper of DWA [12] an admissible velocity pair is described as: "A pair (V,w) is considered admissible, if the robot is able to stop before it reaches the closest obstacle on the corresponding curvature.".

$$V_a = \{(V,w) | V \leq \sqrt{2min_d(V,w)\dot{V}_{break}} \\ \wedge w \leq \sqrt{2min_d(V,w)\dot{w}_{break}}\} \quad (4)$$

C. Objective function calculation

As noted before, DWA uses three components for evaluating the velocity pairs. One of them is a distance function that penalizes velocities which result in dangerous trajectories close to obstacles. On the other hand, FGM already ensures the robot safety as a result of directing the robot to the largest gap center available. Therefore, the distance function of DWA becomes redundant since FGM is very effective on the calculation of a safe heading direction.

The velocity function ensures that the robot operates at a maximum admissible linear speed. This evaluation function is normalized and calculated as shown in Eq. (5). This function provides the speed maximization effect to the objective function except it is near to goal position.

$$vel(V,w) = \begin{cases} \frac{V}{V_{max}} & \text{, if robot is far from goal} \\ 1 - \frac{V}{V_{max}} & \text{, if robot is near to goal} \end{cases} \quad (5)$$

The heading function compares the velocity pair's final heading angle and guide angle obtained from FGM. This angle difference is used to generate a heading score. This function is normalized and calculated as shown in Eq. (6). In this equation $\Delta\theta$ represents angle difference between these orientations.

$$head(V,w) = 1 - \frac{|\Delta\theta|}{\pi} \quad (6)$$

The FGM-DW's objective function which is a composition of velocity and heading functions is illustrated in Eq. (7).

$$G_{new}(V,w) = \beta head(V,w) + \gamma vel(V,w) \quad (7)$$

The FGM-DW approach is implemented in the environment which is previously illustrated in Fig. 5 to show differences between conventional FGM and FGM-DW methods. The FGM-DW's path and applied linear velocities are shown in Fig. 6 and Fig. 7 respectively. The FGM-DW method gives suitable results while the robot is moving in narrow passages. The proposed FGM-DW approach decreases the robot speed in narrow passages and increases it in wide regions by the help of DW part. If robot approaches to goal region less than the limit distance (0.5 meters in simulations), this method rewards low speeds more than higher ones. This formulation prevents the robot from passing the goal region.

V. Simulation Results

Simulations are implemented with the mathematical model of the Turtlebot platform [17] which is a differential drive mobile robot under the ROS environment. A proportional angle controller is used with a conventional FGM method to compare with the new FGM-DW method. This controller drives robot at constant linear speed and angular speed proportional to angle difference between robot orientation and guide angle obtained from FGM. This basic proportional controller is shown in Eq. (8).

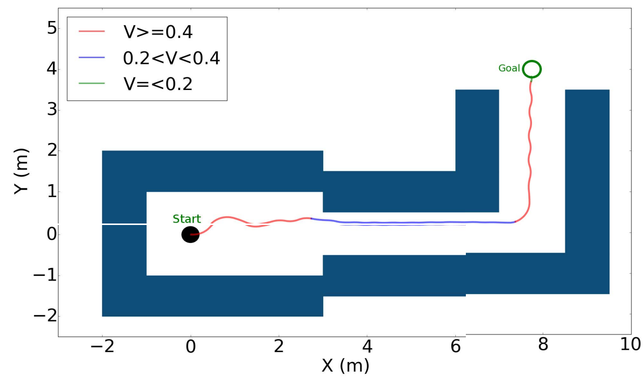


Fig. 6: The path followed by robot after repeating simulation with FGM-DW method.

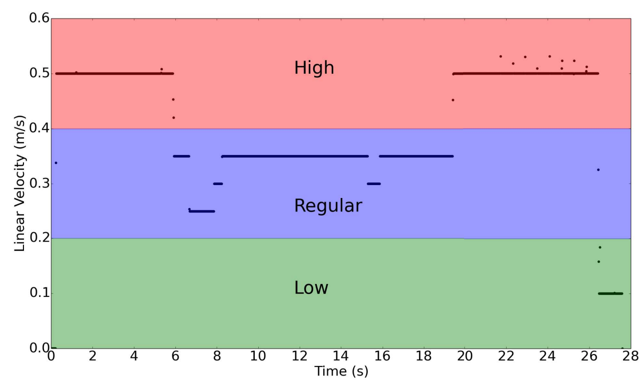


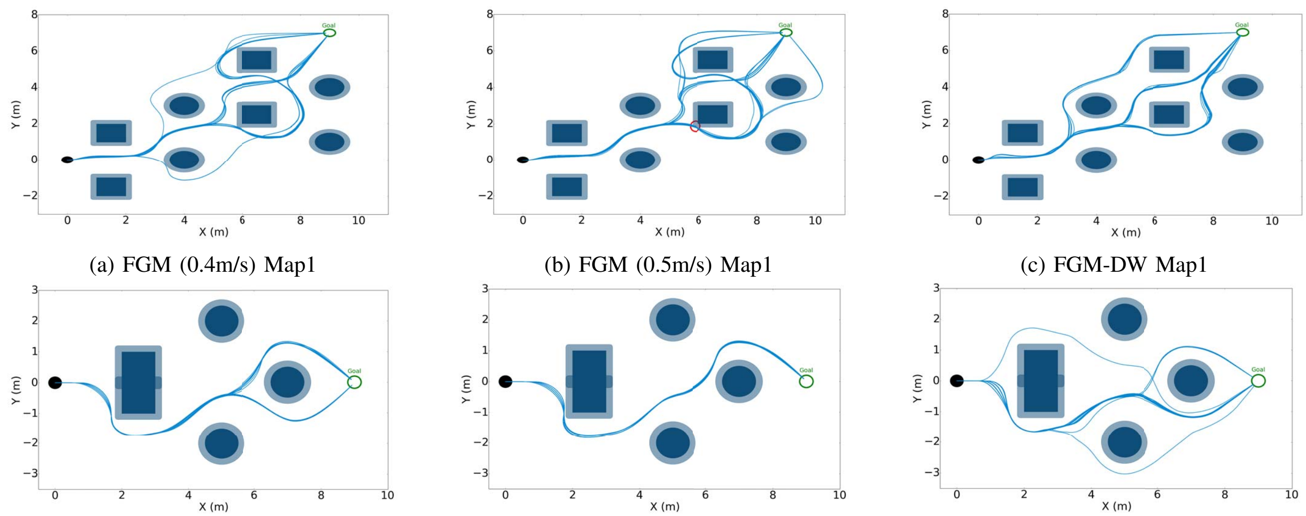
Fig. 7: Applied linear velocities over time obtained from the simulation shown in Fig. 6.

$$\begin{aligned} V &= Constant \\ w &= K_p(\theta_{guide} - \theta_{current}) \end{aligned} \quad (8)$$

The FGM-DW and FGM approach which is controlled by a P controller are implemented in Gazebo for two distinct environments. Over 25 simulations, the paths followed by a robot are shown in Fig. 8. The selected parameter values FGM-DW simulations are; α=1, β=0.6 and γ=0.4. These values are determined with an ad hoc basis because their priorities differ according to the navigation problem. The FGM approach only uses the α parameter. This parameter is determined the same as in the FGM-DW method (α=1). Simulations are implemented in a computer which has 4 Gb of memory and an i5 2.5 Ghz processor, using the Ubuntu operating system. The methods are implemented at a 5Hz operation frequency. For better comparison, performance measures (minimum distance to obstacles, average distance to obstacles, average reaching time) are calculated and shown in Table I and II.

VI. Conclusion

It is shown that, the proposed FGM-DW method solves the obstacle avoidance problem with combining FGM and



(a) FGM (0.4m/s) Map1 (b) FGM (0.5m/s) Map1 (c) FGM-DW Map1

(d) FGM (0.4m/s) Map2 (e) FGM (0.5m/s) Map2 (f) FGM-DW Map2

Fig. 8: Blue lines indicate paths followed by obstacle avoidance algorithms under 25 simulations. An observed collision is shown in a red circle.

TABLE I: Map1 results obtained from 25 simulations

Map1	Min. Dist. to Obstacles	Avg. Dist. to Obstacles	Avg. Reaching Time
FGM (0.5m/s)	0.185m	0.866m	31.657s
FGM (0.4m/s)	0.217m	0.863m	41.079s
FGM-DW	0.383m	1.060m	30.901s

TABLE II: Map2 results obtained from 25 simulations

Map2	Min. Dist. to Obstacles	Avg. Dist. to Obstacles	Avg. Reaching Time
FGM (0.5m/s)	0.238m	0.834m	23.875s
FGM (0.4m/s)	0.316m	0.852m	28.369s
FGM-DW	0.427m	0.917m	25.875s

DWA methods and is safer than the original FGM. Taking robot dynamics and collision check process into consideration allows smooth and safe navigation in configuration space. The FGM-DW intelligently sets the robot's speed according to the environment and its own dynamics. Furthermore, if the robot is close to goal, a slowing down process prevents over shooting the goal region.

As explained before, this method recursively calculates admissible velocity pairs for safe navigation. In narrow passages, the FGM-DW method prefers low speeds, on the contrary it prefers appropriate maximum speeds. This method has three main coefficient, namely α, β and γ. First coefficient α provides safety, β and γ parameters are trade-off between linear velocity magnitude and goal directness.

As can be seen in the Fig. 8, a robot controlled by FGM-DW method passes distant from obstacles. Table I and II results validate this issue. The tables give information about the results of two constant speed FGM and proposed FGM-DW approaches for two different maps. The minimum distance to obstacle is the minimum measured distance from the robot to the nearest obstacle along the whole simulation. The average distance values from robot to nearest obstacle and average reaching time for the whole simulations are also compared in tables.

According to Table I and II, FGM-DW's minimum distance to obstacle value is even improved than the slower constant speed FGM simulation for both of the maps. The FGM-DW's average linear speed is calculated as 0.44m/s where the maximum velocity limit is 0.5m/s. The FGM-DW does not guarantee shortening the path, but it ensures safe, smooth and fast navigation. Although the FGM-DW is safer than both FGM(0.4m/s) and FGM(0.5m/s), its average reaching time is somewhere between fast and slow FGM as shown in Table II. Besides this, Table I shows that the FGM-DW method gives better arrival time results than both of the other methods for the first map, even the average speed is between 0.4m/s and 0.5m/s. The reason can be seen easily in Fig. 8. When we look at the trajectories, the FGM-DW chooses shorter paths compared to both slow and fast FGM simulations. Since the total path is short, the average reaching time is shortest, even FGM-DW's average speed is lower than the FGM (0.5m/s) path.

Also, the FGM-DW method could be implemented in non-circular robots. Obstacle enlargement method in non-circular robots differs from circular robots. Robot constraints and kinematics should also be considered in order to implement this method. Consequently, there is no theoretical limit to the use of this method in non-circular robots.

In conclusion, the proposed FGM-DW method improves conventional FGM in terms of safety and fast navigation. It also takes robot dynamics into account thus this method generates smooth and convenient navigation. Also FGM requires external planners for linear and angular speed determination which is previously proposed in [18]; however the FGM-DW method includes its own planners ensured by the DWA method. The DWA controller used in this method can also control directional obstacle avoidance methods which are previously proposed in [3], [8].

REFERENCES

[1] Kavraki, Lydia E., et al. "Probabilistic roadmaps for path planning in high-dimensional configuration spaces." IEEE transactions on Robotics and Automation 12.4 (1996): 566-580.

[2] LaValle, Steven M. "Rapidly-exploring random trees: A new tool for path planning." (1998).

[3] Khatib, Oussama. "Real-time obstacle avoidance for manipulators and mobile robots." The international journal of robotics research 5.1 (1986): 90-98.

[4] Lozano-Perez, Tomas. "Spatial planning: A configuration space approach." IEEE transactions on computers 100.2 (1983): 108-120.

[5] Borenstein, Johann, and Yoram Koren. "The vector field histogram-fast obstacle avoidance for mobile robots." IEEE Transactions on Robotics and Automation 7.3 (1991): 278-288.

[6] Ulrich, I., Borenstein, J., VFH+: Reliable Obstacle Avoidance for Fast Mobile Robots, in Proceedings of the International Conference on Robotics and Automation (ICRA 98), Leuven, Belgium, May 1998.

[7] Minguez, J., Montano, L., Nearness Diagram Navigation (ND): A New Real Time Collision Avoidance Approach, in Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Takamatsu, Japan, October 2000.

[8] Minguez, Javier. "The obstacle-restriction method for robot obstacle avoidance in difficult environments." 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2005.

[9] Sezer, Volkan, and Metin Gokasan. "A novel obstacle avoidance algorithm: Follow the Gap Method." Robotics and Autonomous Systems 60.9 (2012): 1123-1134.

[10] Simmons, R., The Curvature Velocity Method for Local Obstacle Avoidance, in Proceedings of the IEEE International Conference on Robotics and Automation, Minneapolis, April 1996.

[11] Gal, Oren, Zvi Shiller, and Elon Rimon. "Efficient and safe on-line motion planning in dynamic environments." Robotics and Automation, 2009. ICRA'09. IEEE International Conference on. IEEE, 2009.

[12] Fox, D., Burgard,W. and Thrun, S., The Dynamic Window Approach to Collision Avoidance. IEEE Robotics and Automation Magazine, 4:23-33, 1997.

[13] Brock, Oliver, and Oussama Khatib. "High-speed navigation using the global dynamic window approach." Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on. Vol. 1. IEEE, 1999.

[14] M. Zohaib, M. Pasha, R. Riaz, N. Javaid, M. Ilahi, and R. Khan,"Control strategies for mobile robot with obstacle avoidance," Journal of basic and Applied Scientific Research, vol. 3, no. 4, pp. 1027-1036, 2013.

[15] Quigley, Morgan, et al. "ROS: an open-source Robot Operating System." ICRA workshop on open source software. Vol. 3. No. 3.2. 2009.

[16] Koenig, Nathan, and Andrew Howard. "Design and use paradigms for gazebo, an open-source multi-robot simulator." Intelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on. Vol. 3. IEEE, 2004.

[17] Gerkey, Brian, and Ken Conley. "Robot developer kits." IEEE Robotics and Automation Magazine 18.3 (2011): 16-16.

[18] Sezer, Volkan. "Combined fuzzy approach for online speed planning and control with real vehicle implementation." International Journal of Vehicle Design 68.4 (2015): 329-345.