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OBSTACLE AVOIDANCE SYSTEM FOR AUTONOMOUS MOBILE: A REVIEW

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ABSTRACT

Recent advancements in the field of autonomous vehicles have attracted a lot of interest which indirectly, increased the amount of research and development that went into autonomous mobile robots. Unlike older industrial robots, which have limited mobility and capabilities, current autonomous robots are capable of autonomous movement and navigation, including path planning and obstacle avoidance. These robots can perform tasks that humans are unwilling to perform. Obstacle avoidance system for autonomous mobile robots especially Unmanned Ground Vehicles (UGVs), is one of the main key structures to a successful application of path planning and navigation. This paper presented various types of existing methods of collision avoidance systems or techniques used for mobile robots especially for Unmanned Ground Vehicles (UGVs) and the limitations of each method.

1.0 INTRODUCTION

In today's world, the growth of the technologies of autonomous vehicles has been increasing rapidly. The amount of research and work done within these technologies and industries was overwhelming. Indirectly, the research in wheeled mobile robot systems has also been actively explored by researchers from all around the world. Rather than the traditional industrial robots, which have low mobility and abilities, modern autonomous robots nowadays consist of independent movement and navigation such as path planning and obstacles avoidance. These robots can complete tasks that humans are not willing to do.

The potential applications of intelligent robots may be useful for service robots in various places, for example, offices, factories, and hospitals. These robots also can be applied especially in operating in hazardous areas that cannot be accessible to humans. In that sense, unmanned ground vehicles (UGVs) specifically autonomous unmanned ground vehicles are one of the emerging fields of robotics [1-2]. UGV systems have gained a lot of attention in many applications these past decades such as military operations, search and rescue missions, nuclear areas, transportation, and even in planet exploring.

Moreover, with the continuous development of human exploration activities, these robots will be able to complete a special task which involves high-intensity and intricate tasks. The UGVs have a wide range of implementation prospects, able to replace humans in becoming the first responder for a natural disaster [3]. Obstacle avoidance system (OAS) is one of the main key structures to a successful application of mobile robot systems or in this case the UGVs. The obstacle avoidance system can be classified as the backbone of autonomous control as it makes the robot able to travel the shortest path without any collision to the designated destination. Most of the current mobile robots have some kind of collision avoidance features embedded with it. Varying from the basic algorithms which stop the movement of the

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robots whenever the system detected the obstacles, through the sophisticated algorithms or methods that change the direction of the robot to avoid a collision.

In case of robots autonomous navigation, obstacle avoidance systems play an important role in maneuvering the robots, especially in a completely unknown environment [4]. Local environment information from the sensors is the main key feature to a successful OAS. In this current wave of modern technologies, various types of sensors were used for the robot OAS due to the rapid development of science and technology. From the simplest of ultrasonic and infrared sensors to the complexity of lidar, vision, and inertial sensors. The latest OAS have evolved not only on the detection of obstacles, but have been more intuitive and complex as the systems also include some kind of quantitative measurements such as the dimensions of the obstacles [5-8].

2.0 OBSTACLES AVOIDANCE METHODS

In the last two decades, the development of path planning methods and algorithms for the autonomous navigation system of mobile robots especially UGVs, have been rising rapidly [9]. However, the path planning system and obstacle avoidance system are two different systems but correlated in some ways [10-11]. The OAS is just a part of the path planning system's structure, but it is also considered as an independent system structure. The purpose of an OAS is to avoid collision from obstacles, on the other hand, the objective of the path planning system is to navigate the robot from one point to another point without any unintended collisions [12-13]. Based on the feedback inputs from the sensors, the obstacle avoidance algorithms can modify the trajectory of the robots in real-time, therefore, it can avoid collisions with the obstacles found in its path. Moreover, all types of OAS are constructed and developed based on these two concepts of obstacle detection; ranged-based obstacle detection and appearance-based obstacle detection [4, 12].

In range-based systems, obstacles are defined as objects within the maximum distance from the robots. Meanwhile, appearance-based systems define the obstacles when an object which are different structures from the surface. While in the case of range-based, the sensors are not only able to scan the area and detect any obstacles, but also calculate, and provide the distance between the mobile robot and the obstacle. In appearance-based, the physical features of the obstacle are detected by using image processing which is taken from the environment. Vision sensors provide a large amount of information from the environment that is useful for obstacles detection [6-7, 17]. However, this large quantity of data also represents great computational complexity for processing the circuitry of the mobile robot [18]. This section of the paper summarizes some of the obstacle avoidance methods including path planning techniques, that have been developed, from the basic methods to the latest and sophisticated methods of the obstacle avoidance system [5, 19].

2.1 EDGE – DETECTION METHOD

One of the ways to extract only the crucial details for appearance-based obstacle detection is the Edge-Detection method. Edge detection is one of the key parts of the image processing systems of mobile robots' navigation. It allows the extraction and display of features such as curves, lines, and angles to identify images from the environment. The main idea in the edge detection process is based on an abrupt change in the intensity of pixels between adjacent pixels in the image. The edge represents a location that forms the border between the pixels of high and low intensity [2, 22]. The edge is shown by a rapid changes within the image that indicates the typical features, and can thus be described as a group of pixels whose environmental intensity varies continuously [23]. The characteristic of edge detection mostly depends on light conditions, the presence of objects of similar magnitude, the quality of edges in the scene, and noises. An "optimal" edge detector can be defined as [21]:

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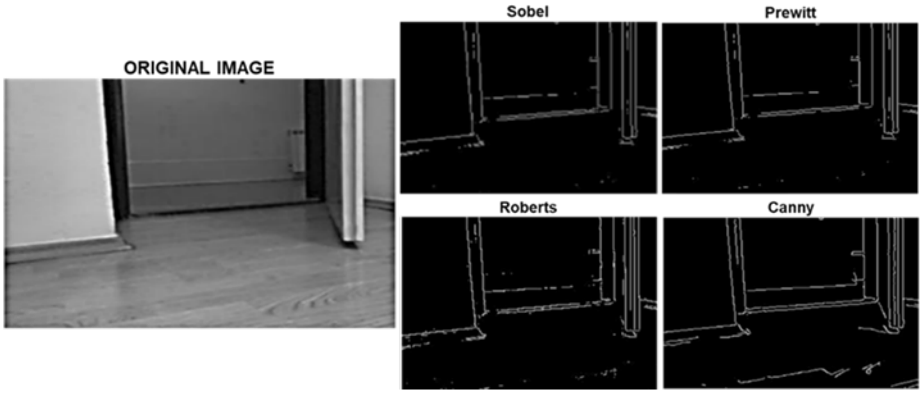

Figure 1. Example of Edge-Detection method using different algorithms with vision sensor (camera) [5]

- *Good detection* – The algorithm should mark as real edges in the image as possible.
- *Good localization* – Marked edges should be as close as possible to the edge in the real image.
- *Minimal response* – A specific edge in the image should only be visible once, and image noise should not generate false edges if possible.

In the edge-detection method, there is four most commonly used algorithm which is the *Sobel, Prewitt, Roberts,* and *Canny* algorithm [21]. These edge detection techniques have been utilized in a variety of systems to detect edges in a variety of settings and scenarios. In order to compute the largest change in the gradient at an edge, the Sobel, Prewitt, and Roberts methods apply derivatives on an intensity map [2]. By eliminating practically all non-edges and enhancing the localization of all recognized edges, the *Canny* method might achieve a low error rate which are more favourable [14, 24].

For other edge-detection approach such as (Ranged-based obstacle detection), it takes a panoramic scan of its environment using ultrasonic sensors in which, the robot will remain stationary until the process ends [25]. In this method, the position of the vertical edges of the obstacle is determined by an algorithm and then moves the robot towards either one of the "visible" edges. The line connecting two visible edges is considered to represent one of the boundaries of the obstacle. This method was used in previous research [26], as well as in several other works [20], all using ultrasonic sensors for obstacle detection.

2.2 Certainty Grid

At the Carnegie-Mellon University (CMU), a grid-type world model for the probabilistic representation of obstacles has been developed which is called the Certainty Grid. This world model is designed to accommodate all of the sensor’s inaccurate data, such as ultrasonic sensor distance readings. The robot's work area is represented in the certainty grid by a two-dimensional array of square elements known as cells.

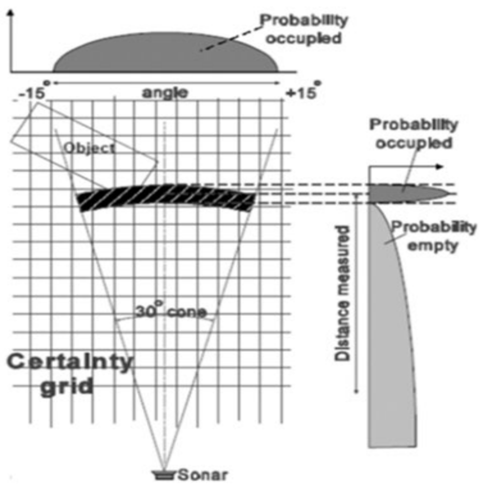

Figure 2. Example of certainty grid for the ultrasonic sensor with the CMU method

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In this grid, each cell contains some values that indicate the degree of confidence that an obstacle presents within the cell area, which is called the certainty value (CV). With the CMU method, the values will change or be updated time after time by a probability function that includes the variety of characteristics of a given sensor. For example, a common ultrasonic sensor has a conical field of view that returns a radial measure of the distance to the nearest barrier or object within the cone but does not identify the object's angular location [20, 25].

One of the most crucial applications of Certainty Grid is to construct and maintain a probabilistic, geometric map of the mobile robot's environment, as it moves, it has to fuse data in the same cell simultaneously from other sources and also can update the probability value in each cell while new input or information came by the robot movement [27]. Next, the robot moves to a new location and stop, then this procedure will repeat accordingly. After the robot traverses a room in this manner, the resulting certainty grid represents a fairly accurate map of the room. A global path-planning method is then employed for off-line calculations of subsequent robot paths [28-29].

2.3 Potential Field Method (PFM)

The idea of imaginary forces acting on a robot has been suggested by Khatib [22, 30] which is called Potential Field Method (PFM). In this method, obstacles exert repulsive forces, while the target applies an attractive force to the robot as shown in Figure 3. A resultant force vector, comprising the sum of all forces which are the repulsive forces and attractive forces, is calculated for a given robot position. With resultant force vector as the accelerating force acting on the robot, the robot's new position for a given time interval is estimated, and the algorithm is repeated [31].

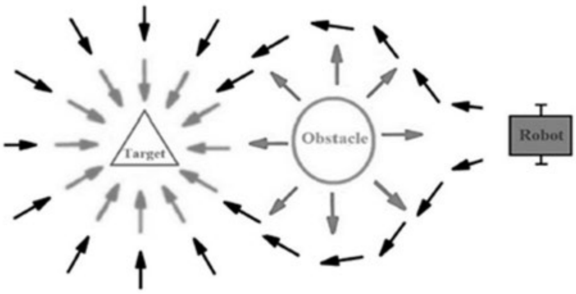

Figure 2. Potential Field Method model by Khatib [36]

Thorpe [24] has extended the PFM to off-line path planning, whereas Krogh [33] has enhanced this notion by taking into consideration the robot's velocity in the vicinity of obstacles. As a result, Krogh and Thorpe [34] propose a combined method or algorithm for the global and local path planning systems that use a novel approach known as the “Generalized Potential Field”. Newman and Hogan [34] integrate individual obstacle functions with logical operations that present the construction of potential functions. Common to these methods is the prediction of a known and prescribed world model, in which obstacles and the robot's path are generated offline by predefined geometric shapes [35].

While each of the above methods features significant modification, none have been implemented on a robot with real-time sensory data. On the other hand, Brooks [36] and Arkin [33] used the PFM on experimental mobile robots which are equipped with a ring of ultrasonic sensors. In Brooks implementation, the repulsive force vector is from each ultrasonic range reading. The robot will stop and turn to the direction of the resultant force vector, if the weight of the sum of the repulsive forces exceeds a certain threshold, then moves on [37]. However, only one set of range readings is included in this application, and earlier readings are lost. Arkin [20] use a similar technique, and one of them was able to negotiate an obstacle course at 0.12 cm/sec [20].

3.0 VIRTUAL FORCE FIELD

The Virtual Force Field (VFF) method is specially designed for real-time obstacle avoidance with fast mobile robots. Bornstein’s research [38] on real-time OAS for mobile robots is based on this method. This method enables the robots to navigate and move with fast, continuous, and smooth motion through any unexpected obstacles. The combination and improvement of the Certainty Grid method and the PFM are where the VFF method came from [20, 37].

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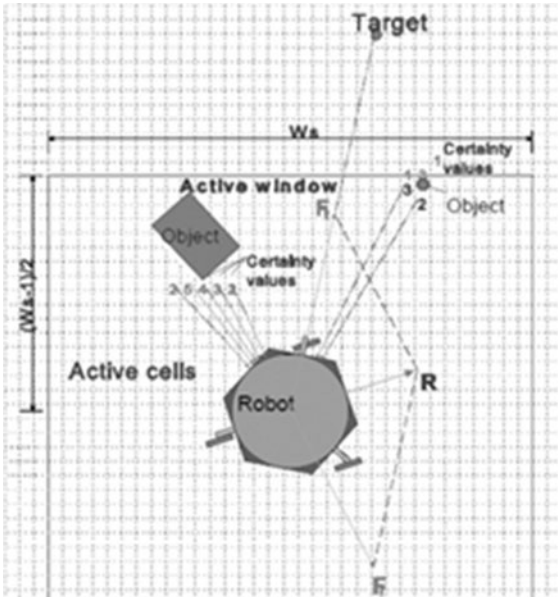

Figure 4. The Virtual Force Field concept

The uses of histogram grid are involved in this method for representing the robot's work area. The certainty value, C (i, j) in any of these cells indicates the degree of confidence that an obstacle is in the cell. The range readings map into the Certainty Grid during the movement of the robots. At the same time, after inspecting a frame region in the Certainty Grid, this algorithm will repel the robot away from the occupied cells. The amplitude of the repelling force is inversely proportional to the square of the distance between the cell and the robot, and is affected by the number of occupied cells in the inspected frame [39-40].

3.1 Vector Field Histogram (VFH)

The previous VFF method still has its disadvantages even though the method performs quite fast. The implemented testbed shows that often the robot would not move in a situation when there are two or more obstacles that are close to each other. This is because of the repellent effect from both sides, which causes the robots to repel away. The PFM also experienced these kinds of problems [41]. Therefore, to solve these issues with VFF, Borenstein, and Koren [42] designed and proposed the Vector Field Histogram (VFH) method [43]. This method uses a two-stage data reduction methodology rather than the single-step strategy employed by the VFF. As a result, there are three levels of data representation. The environment in this method is being represented using a 2D histogram grid, plus the polar histogram, which is reduced to a single dimension, is built around the position of the robot in a certain moment. The polar obstacle density is the sector presented in the polar histogram [44].

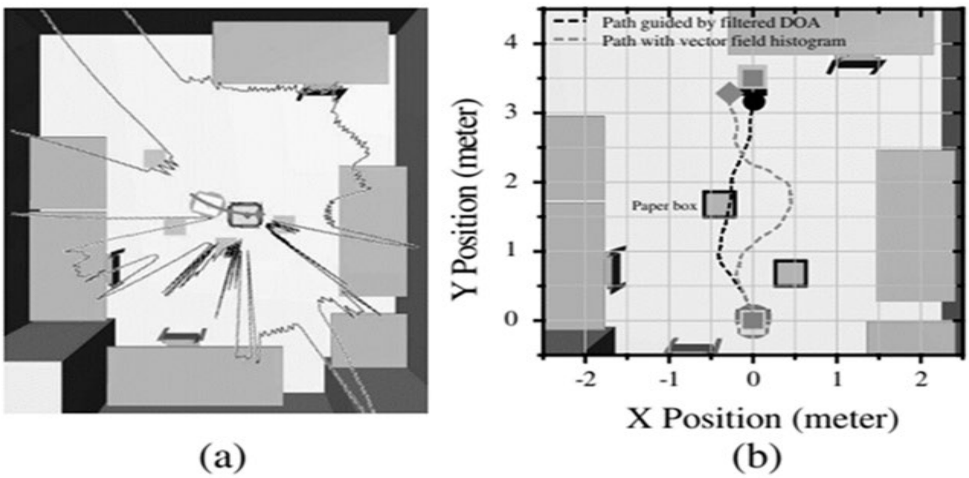

Figure 5. (a) Vector field histogram from the distance estimation by sonar sensor array (b) Results of robot docking [45]

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The sector with the least concentration of obstacles will be the direction of the robot. The robot's sensors will keep updating the histogram grid which is the map, with the information that has the range or distance between the obstacles and the robot. Figure 5 above shows the result in [45] with the application of the VFH, the algorithms will update the estimated distance data by detecting the obstacles within the range while the robot moves. Figure 5(a) displays a VFH in Polar coordinates using calculated distances to surrounding obstacles. Meanwhile in Figure 5(b), from the vector field, the robot can navigate across the room with a collision-free path to the targeted destination as shown. The robot collides with the boxes using the previously predicted degree of arrival (DOA). The VFH algorithm, on the other hand, allows the robot to effectively avoid the boxes and arrive at the target position [45].

3.2 Vector Field Histogram Plus (VFH+)

The VFH+ approach is an improved version of Borenstein and Koren's original VFH method for real-time local obstacle avoidance [4, 26]. This method was used to create a particular form of mobile robot known as the Guide Cane project. This project is a novel guidance device for the blind that was invented in 1998 [38]. To calculate the new direction of motion, the VFH+ approach uses a four-stage data reduction process. The two-dimensional (2D) map grid is reduced to one-dimensional (1D) polar histograms surrounding the robot's temporary location in the first three stages [46]. In the fourth stage, the masked polar histogram along with a cost function, the algorithm will select the most suitable direction for the robot [9, 15].

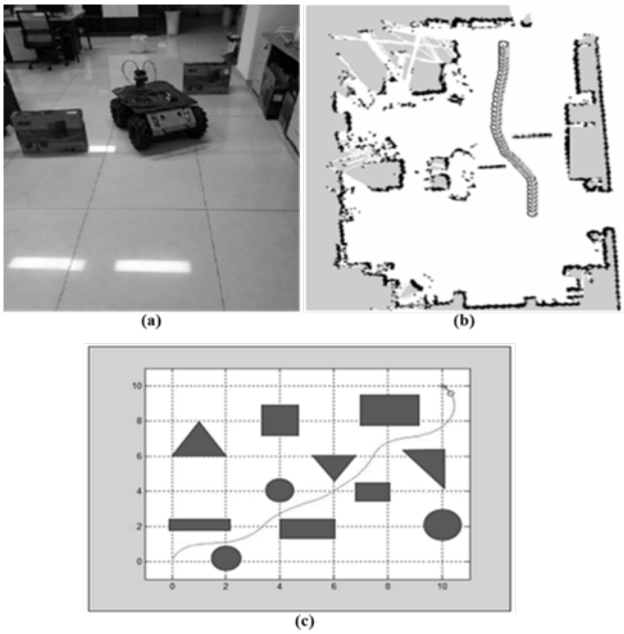

Figure 6. (a) Test of Husky, (b) Simulation result, (c) Experimental result. [4]

In [4], the VFH+ was used on a wheeled mobile robot called Husky shown in Figure 6(a) for the OAS. Figure 6(b) shows that the algorithm developed in [4], the robot can not only reach the target point safely but also do not have significant steering fluctuations plus able to achieve a smooth obstacle avoidance effect. In this study, laser radar was utilized to create a global map to identify the robot, and temporary impediments were added to the map. The experiment was conducted in the laboratory, with the robot moving from its starting point to a pre-determined destination while encountering momentary obstacles along the way [4, 38].

The obstacle avoidance test result is shown in Figure 6(c). The VFH+ method will try to avoid the loss of obstacle details. This method will detect the obstacle boundaries to obtain the reference direction of the robot. This approach does not have to specify a threshold in advance, unlike the VFH algorithm and its family [38]. This is because this method could remove the blindness to determine the feasible robot direction as reference is given to the border conditions of barriers. This will greatly improve the efficiency of finding the reference direction. At the same time, the security of the robot will be guaranteed even though there will be the existence of various constraints [4, 47].

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3.3 Fusing PFM & VFH

The work in [48], the proposed method for OAS is by fusing PFM and VFH. This method used the concept of the obstacle, steering, and integrated force fields. The obstacle force field is generated by the range data obtained from a sensor that is placed on the mobile robot, based on this research [48], a laser range finder (LRF) mounted on the UGV. The steering command is the element that created the steering force field. The force is either transmitted from the remote-control station (RCS) or calculated in the autonomous navigation system (ANS) of the unmanned ground vehicle [49].

Overlapped these two fields by using the integrated force field that will produce the modified steering, velocity, and emergency stop commands. These commands were created to enable the robots to avoid collision and follow a planned path [48, 50-51]. The usefulness and practicality of this method were verified and proven in [48]. In this research, the mobile autonomous robot is shown in Figure 7(b) was safely and avoids not only static obstacles but also dynamic obstacles such as humans and cars. Figure 7(a) shows the test setup in this project in which several obstacles were placed on the flat lawn ground [48].

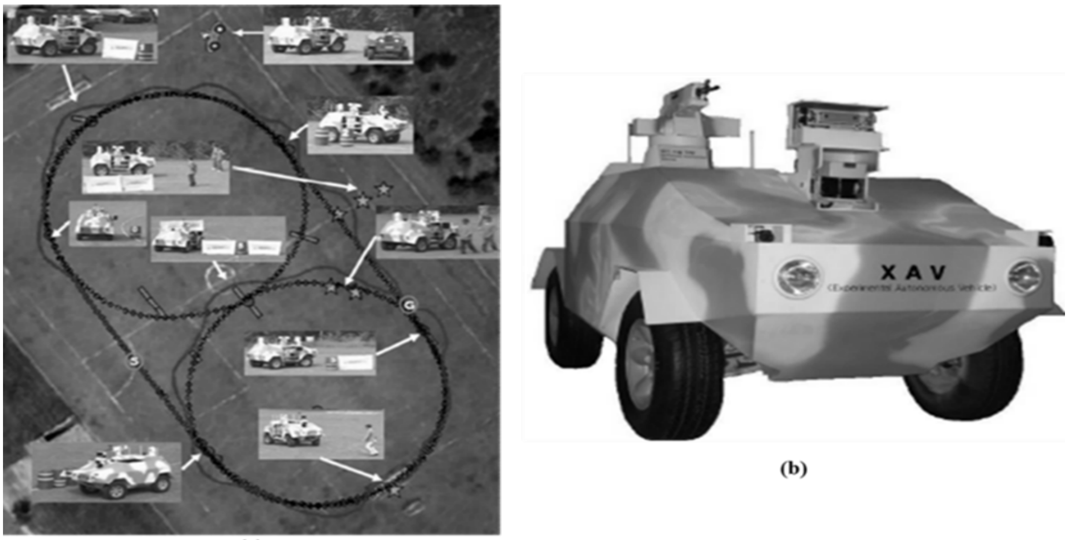

Figure 7. (a) The static and dynamic test setup, (b) The eXperimental Autonomous Vehicle (XAV) [33, 35]

4.0 DYNAMIC WINDOWS APPROACH

In contrast to VFF and VFH methods, the Dynamic Window Approach (DWA) [52] is another method for reactive OAS handling with the kinematical and dynamic constraints of the mobile robot. The method can be described as a search for commands algorithm that will measure the velocities of the vehicle which are then passed to the velocity space [8, 32]. The trajectory element of the robot is referred to the sequence of circular arcs.

The arcs are described as a velocity vector (*vi*, ω*i*), in which *vi* denotes the translational velocity and ω*i* stands for the rotational velocity, together it represents the search space [15-16, 53].The dynamic window is formed from the reduced search space, which included the trajectory formed by the circular arcs and is defined by the velocity vector. The Dynamic window denoted by V_d, the area V_a in which the vehicle can stop and avoid a collision, the space of possible velocities represented by V_s which all intersected with the region V_r located in the dynamic window [54-55], defined as:

$$V_r = V_s \cap V_a \cap V_d \quad (1)$$

However, the DWA method still has its flaws according to Li [56], where it tries to make a balance between arriving target and avoiding collision whenever it has the problem of using unsuitable weigh parameters. Therefore, based on Li [56], a new method had been proposed using a similar approach to the DWA which is called Collision Avoidance Dynamic Window Approach (CADWA). Its only purpose is to

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eliminate both parameter tuning, reduce collision risk between agents, and local minimum. The CADWA algorithm is an independent module that serves the existing formation control algorithm.

Figure 8 shows how the CADWA algorithm works, which consists of collision risk detection and collision avoidance, the two parts marked in red blocks. The functionality of smaller parts of each part was discussed in the work [56]. It's important to keep in mind that even after subtracting the CADWA algorithm from the whole system, the usual formation control method stays unchanged. It demonstrates that this approach may be incorporated into any current formation control technique without affecting the original scheme [9, 15-16, 57].

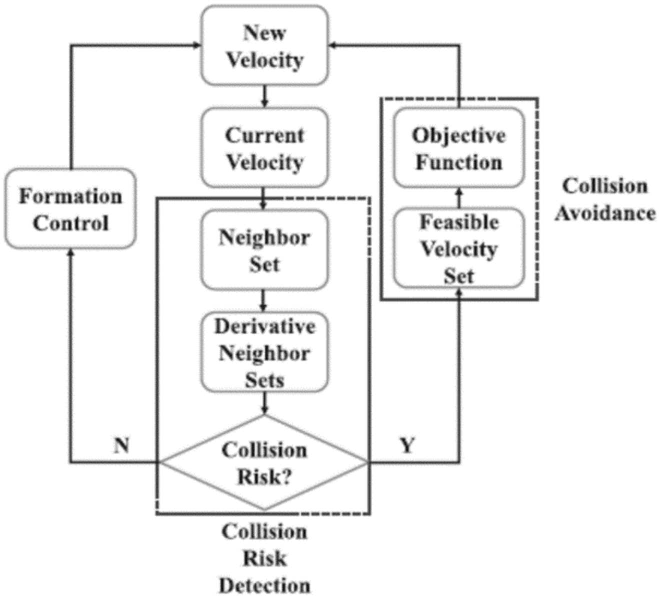

Figure 8. CADWA Flowchart Algorithm

4.1 Nearness Diagram

The research given in [11, 23, 58] focuses on the issue of OAS in a congested setting. The Nearness Diagram (ND) approach explored the divide and conquer concept, which divides the surroundings into sections to show where barriers are located. These experiments reveal that the ND technique solves the local minima trap by avoiding it, but only if the local minima trap is completely apparent to the sensors. The use of predefined parts of characteristic states consisting of various problems and the algorithm corresponding actions is how this method's concept works.

The algorithm is executed, the current state is defined based on sensory data, and the relevant action is carried out as shown in [11, 24]. It analyses the obstacles information in the field of view to determine the free walking region that is both passable to the robot and nearest to the goal location. The ND approach establishes a collection of situations based on safety requirements and designs the action to the associated situation. The ND method can overcome some of the traditional constraints of current reactive navigation, particularly in terms of avoiding local trap situations in the field of view. Its situation-action paradigm also makes robot navigation much easier as it has a low computational load. The work in [59], uses Motion Generator and Shape Corrector by applying the ND approach to kinematic, dynamic, and geometrically constrained mobile platforms, but resulted in the robot moves at a lower speed [54].

4.2 Curvature Velocity Method

The Curvature Velocity Method (CVM) [60] involves the dynamic constraints of the robot allowing it to navigate fast in a dense environment. Rather than operate in the Cartesian or configuration space, the main distinction is, that this method operates in the velocity space of the robot and chooses commands by maximizing an objective function that will create trade-off between vehicle safety, speed, and goal-directed [61-62].

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The method presumes that the robot can travel along arcs of circles which means the algorithm can control both rotational and translational velocities but nevertheless cannot turn instantaneously. This formulation includes various types of non-holonomic robots, differentially steered robots, and synchro drive robots. This CVM disregards the effects of accelerations and the effects of acceleration are not taken into account and ultimately, mobile robots traveling at walking speeds provide a decent approximation [54, 61]. The CVM tackles the challenge of local obstacle avoidance in fully unknown settings for mobile robots. Several other researchers have been studied with this kind of issue, based on several requirements that are common to most existing methods [61], namely:

- The robot should navigate safely, even in the face of noisy sensors errors.
- The robot should be goal-directed while trying to avoid obstacles.
- The method must be computationally efficient, to run in real-time on-board the robot.

In addition, several requirements are often not addressed by other methods, the dynamics of the robot should be included which will enable the robot to travel at high speeds in crowded environments. The process should explicitly attempt to maximize robot progress and allow the approach to control the robot's direction and speed simultaneously [61].

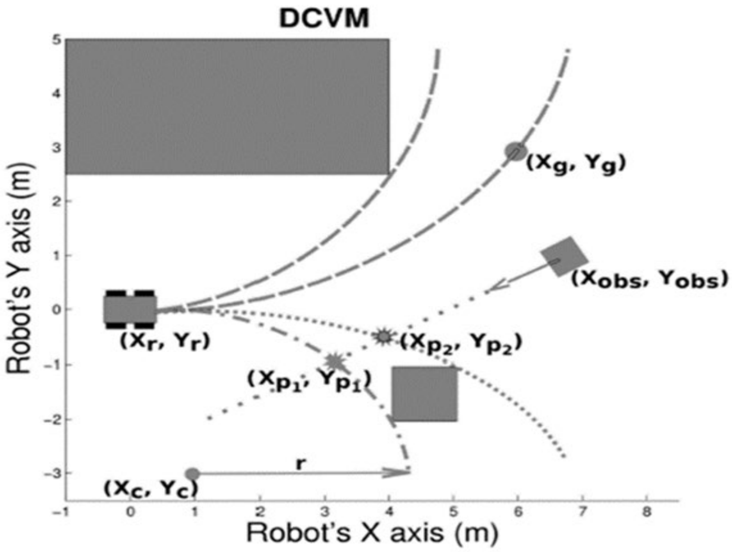

Figure 3. DCVM scheme based on [29]

Finally, an extension of a CVM algorithm which is to deal with dynamic obstacles called, Dynamic Curvature Velocity Method (DCVM) has been developed and has been proven that it can avoid obstacles in a safer and better way than previous obstacle avoidance algorithms since its performance has been tested in simulated and real environments [63-64]. The Lane Curvature Method (LCM) [38] is also an extension to CVM to address some of its problems. The Beam Curvature Method (BCM), according to [10], has solved the limitations in LCM and can improve the performance of CVM as well as LCM [15, 65]. The Table 1 shown in the Appendix section, will summarizes all the obstacle avoidance methods that are present in this paper in orderly manners. In addition, includes aspects of the region of interest and robot platform compatibility plus the key features for every Obstacle Avoidance (OA).

5.0 LIMITATIONS AND DRAWBACKS

Every innovation proposed has its own imperfection and limitations. Therefore, a few limitations and drawbacks of each obstacle avoidance (OA) method will be present in this section and summed up in Table 2 shown in the Appendix section. In addition, the table includes the aspects of the region of interest and the sensors used for every method. Different methods have a different type of limitations however, some of these methods that have been mentioned in the previous section have the same drawbacks. This is because several of these methods was an evolvement from a simple form to a more complex form.

The Edge-Detection method has two types of approaches, but both have the same drawbacks. A common drawback of both edge-detection approaches is the sensitivity to the sensor's accuracy. Any one

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of these errors can cause the algorithm to determine the existence of an edge at a completely wrong location, oftentimes resulting in highly unlikely paths [66]. The poor directionality limits the accuracy in determining the spatial position of an edge to 10-50 cm, depending on the distance to the obstacle and the angle between the obstacle surface and the acoustic axis [16, 20, 23, 67].

Frequent misreading is caused by either ultrasonic noise from external sources or stray reflections from neighbouring sensors. Misreading cannot always be filtered out and they cause the algorithm to falsely detect edges. Specular reflections occur when the angle between the wavefront and the normal to a smooth surface is too large. In this case, the surface reflects the incoming ultra-sound waves away from the sensor, and the obstacle is either not detected, or "seen" as much smaller than it is since only the part of the surface is detected.

Most of the methods that have been mentioned in the previous section used ultrasonic sensors, therefore similar limitations may or may not occur to these methods that used the same sensor. In Certainty Grid, applications of this method [23-24], the mobile robot remains stationary while it takes a panoramic scan with its 24 ultrasonic sensors. The Potential Field method (PFM) is one of the popular methods in the world of OA and path planning systems. Since many of the existing OA systems were some kind of evolution or derivation from PFM [18, 41]. One of the significant limitations of PFM is the oscillation in the presence of an obstacle. This method tended to cause an unstable motion in the presence of obstacles. A similar yet more severe problem with PFMs is the oscillation in narrow passages [68].

This occurs when the robot travels in narrow, in which the robot experiences repulsive forces simultaneously from the opposite sides. Perhaps the best-known and most cited problem with PFMs is the trap situation due to local minima. This drawback takes place when the robot runs into a dead end, for example, a U-shaped obstacle. Traps can be created by a variety of different obstacle configurations, and different types of traps can be distinguished [1, 69-70]. Given that Vector Force Field (VFF) is sequential from the PFM, this method inherited two limitations which are the oscillation in narrow passages and the trap-situation due to the local minima. Moreover, the VFF method is one of the backbones of the Vector Field Histogram (VFH) method. As a result, this method still has a problem with the trap situation [38, 42]. However, some previous works resolved this situation by applying heuristic or global recovery rules, but it will result in a non-optimal path. This is when the next generation of the VFH method is developed, which is the VFH+ method [9, 16, 66]. This method overcome the previous limitations in favour of an integrated global path planner (GPP).

6.0 CONCLUSION AND FUTURE WORK

This paper has presented various types of methods of collision avoidance systems or techniques for mobile robots especially for Unmanned Ground Vehicles (UGVs). Varying from the basic algorithms which stop the movement of the robots whenever the system detected the obstacles, through the sophisticated algorithms or methods that change the direction of the robot to avoid a collision. In addition, this paper has also summarized each method’s disadvantages and drawbacks, which will make this paper to be a good reference for future research in these issues. However, most of these methods were meant for a UGVs, wheeled-mobile robots to be exact. Tracked vehicle robots are also a type of UGVs which in these past 20 years, there were only a few research or studies on collision avoidance systems for these types of robots. Since these robots were widely used especially in the military, search, and rescue missions, and for policing, therefore, a collision avoidance system will be a significant advancement that can be embedded on these robots.

In conclusion, all the methods and algorithms presented in this paper can be considered as the first basis for any collision avoidance system for mobile robots. Nevertheless, several of these methods have only been tested and proved in the lab, rather than in a real-world setting. As a result, as technology advances, there are numerous ways in which these methods can be improved in the future and eventually, can be used on a mobile robot for a real-life operation.

7.0 ACKNOWLEDGMENT

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