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A comprehensive study for robot navigation techniques

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Abstract: An intelligent autonomous robot is required in various applications such as space, transportation, industry, and defense. Mobile robots can also perform several tasks like material handling, disaster relief, patrolling, and rescue operation. Therefore, an autonomous robot is required that can travel freely in a static or a dynamic environment. Smooth and safe navigation of mobile robot through cluttered environment from start position to goal position with following safe path and producing optimal path length is the main aim of mobile robot navigation. Regarding this matter, several techniques have been explored by researchers for robot navigation path planning. An effort has been made in this article to study several navigation techniques, which are well suited for the static and dynamic environment and can be implemented for real-time navigation of mobile robot.

Subjects: Automation Control; Robotics & Cybernetics; Control Engineering; Systems & Controls

Keywords: Artificial intelligence; neural network; fuzzy logic; AGV

1. Introduction

In modern era, to lower the burden of labor on mankind effortlessly, physical tasks are being performed by machines which were considered to be done by human in the past. Nevertheless, there is a need of special thing that machines not only do physical tasks but also can think and make decision like human being. To make things intelligent and to get this target, artificial intelligence knowledge has got important consideration. Path planning has been considered as



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Wan Rahiman gained his undergraduate degree from Cardiff University, U.K., specializing in Manufacturing Engineering (BEng). Then, he was an engineer with Panasonic Manufacturing Ltd in Cardiff and Lotus Cars Ltd in Norwich for a few years. He joined the Control System Centre, University of Manchester and received his Ph. D. degree in field of Fault Detection and Isolation for Pipeline Systems in 2009. He is currently a senior lecturer with the School of Electrical and Electronic Engineering, Universiti Sains Malaysia (USM), Engineering Campus, Penang, Malaysia. At USM, he serves as Head of Sustainable Platform of Air, Land and Naval (SPALAN) Research Group. His research interests lie in the area of modelling nonlinear systems on range of development research projects, particularly, in drone and autonomous vehicle technologies.

PUBLIC INTEREST STATEMENT

The mobile robot is considered as an autonomous field agent tendency of navigating intelligently anywhere in an environment using control techniques. Many researchers have been doing research in this field to find the smoothest and safest path for mobile robot to pass through the cluttered environment. The paper contains brief study for the methods involve in navigation system along with algorithms used for optimizing the path for mobile robot. In modern days, robots have fundamental importance in every field. The robots are helping humanity to reduce men labor and efforts.

the most-common problem for robot navigation, robots have to move from starting position to goal position via avoiding obstacles. Robots like micro air vehicle (Yan, Liu, & Xiao, 2013), (Schler, 2012), motion robot, wall-climbing robot (Aghababa, 2012; Yilmaz, Evangelinos, Lermusiaux, & Patrikalakis, 2008), and underwater robots have been tested with different algorithms.

In the beginning, the researchers have focused on 2D path planning like Choset (Choset, 2005) researched on 2D path planning therefore avoiding the bio-inspired algorithms. Later on, different surveys were also done regarding the mobile robot in a 2D environment.

Mobile robot navigation is an essential issue in the field of robotics. They are known for their intelligence tendencies. They also cover wide range of applications, such as in transportation, industry, and rescue robots. Path planning is one of the most prominent and essential part of autonomous mobile robot navigation. For the past two decades, researchers are working on path planning problem for which several methods have been developed. Path planning involves the determination of collision-free path from one point to another while minimizing the total cost of the associated path. Depending on the nature of environment, path planning can be divided into *static* and *dynamic* environment. If obstacles change their position with respect to time, it is referred as *static path planning* and if obstacles change their position and orientation with respect to time, then it is referred as *dynamic path planning*. This knowledge can further be divided into *online* and *offline* algorithms. In online path planning, the information about surrounding is obtained from separately attached local sensor installed on robot, then robot construct the map of environment from the information being fed from the locally attached sensors. In offline path planning, robot has complete information of surrounding environment without the aid of sensors. For ensuring the satisfactory navigation, numerous strategies have been proposed up till now.

Ibraheem et al. (Ibraheem & Ajeil, 2018) used the hybridization of Particle Swarm and Modified Bat algorithms to plan the path of robot in static and dynamic environment. The proposed method achieve the multi-objective functions for robot, that is, shortest distance and path smoothness. For obstacle avoidance, they used the gap vector method.

Hassani et al. (AL-Nayar, Dagher, & Hadi, 2019) planned the path of robot in a cluttered environment by using the free segment and turning point strategy. The turning point approach searches for safe path for robot from start point to goal point without colliding with obstacles. In addition, sliding mode controller is also used for stabilization of robot to track the desired trajectory. The proposed method handles two objectives for robot, that is, path safety and path length.

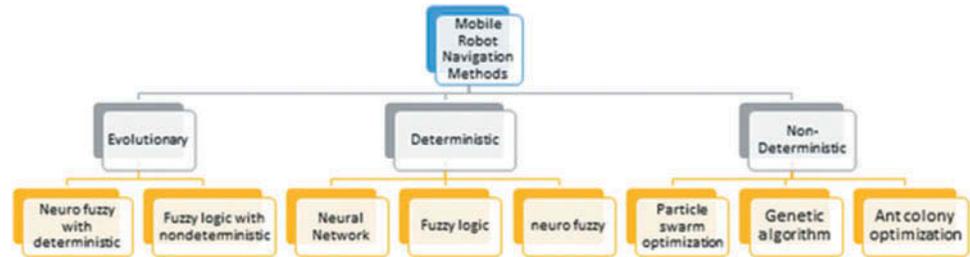
Muna et al. (Hassani, Maalej, & Rekik, 2018) have used the chaotic particle swarm optimization (PSO) and firefly algorithm to solve the multi-objective path planning problem for wheeled mobile robot.

Artificial Intelligence (AI) is the science of understanding and making things intelligent, which helps in making good decision and prove useful in performing task. An intelligent system requires some techniques to solve problems and such techniques are considered as Artificial Intelligence Techniques.

Different AI techniques such as Fuzzy logic system, Neural Network (NN), Neuro-Fuzzy and Computing Techniques like Genetic Algorithm (GA), Bio-inspired Computing Technique, Ant Colony Optimization (ACO), and Particle Swarm Optimization are well known.

The article contains the study of various techniques used for mobile robot navigation system. Obstacle avoidance and path following are considered as basic problems in mobile robotic system. The purpose of navigation is to navigate through cluttered environment in search for optimal path from the start position to target position. The mobile robot navigation has been performed by

Figure 1. Classification for evolutionary, deterministic and non-deterministic methods.



Deterministic and non-Deterministic (Stochastic) Algorithm and their hybridization is called as Evolutionary Algorithm, which is also common in use to solve navigation problem. Figure 1 shows the different methods for Deterministic and non-Deterministic and Evolutionary method.

Navigation can be divided into two types: Global and local Navigation (Maram Alajlan, Koubaa, Chaari, Hachemi Bennaceur, & Ammark, 2001; Sedighi, Ashenayi, Manikas, Wainwright, & Tai, 0000). For global navigation type, prior knowledge of environment should be known, which is also called as Off-line mode for path planning, For example: Dijkstra algorithm (Soltani, Tawfik, Goulermas, & Fernando, 2002), A* algorithm (Liu & Gong, 2011), Visibility graph (Masehian & Amin-Naseri, 2004), Artificial potential field method (Gomez, Martinez Santa, & Martinez Sarmiento, 2013), and cell decomposition method (Park, Kim, & Kim, 2001). For local navigation, also known as On-line mode for path planning in which robot decides its position and orientation and can control its motion using externally equipped sensors for example: Infrared sensor, ultrasonic sensor, LASER, and vision sensor (camera) can be employed to autocorrect the orientation of robot via software, other techniques involves NN (Engedy & Horvath, 2010), Fuzzy logic (Montaner & Ramirez-Serrano, 1998; Zadeh, 1975), Neuro Fuzzy (Zhu & Yang, 2007), PSO (Ahmadzadeh & Ghanavati, 2012), GA (Ghorbani, Shiry, & Nodehi, 2009), and ACO (Garcia, Montiel, Castillo, Sepulveda, & Melin, 2009). They are considered as successfully employed algorithms used by researchers. Local Navigation methods are described as below.

2. Global navigation methods

2.1. A. APF

Artificial Potential Field (APF) is a nature inspired technique. The basic idea of APF is to fill the robot environment with the artificial potential field in which obstacles are repelled using repulsive force and robot is attracted toward the goal using attractive force. The potential field depends on two forces, that is, attractive and repulsive force. The goal produces the attractive force towards robot and obstacles produce repulsive force, which is inversely proportional to the distance from robot to the obstacles and directing toward obstacles. In APF field, robot travels from high potential to low potential. The Potential function can be written for attractive and repulsive forces, as shown in equations 1-5:

$$U(q) = U_{att}(q) + U_{rep}(q) \tag{1}$$

Commonly used attractive potential used is:

$$U_{att}(q) = \frac{1}{2} \zeta \rho^2(q, q_{goal}) \tag{2}$$

where ζ is gain, and (q, q_{goal}) is the distance between robot and the goal.

The attractive force is given as the negative gradient of attractive potential and the attractive force will be considered as zero as it approaches goal.

$$F_{att}(q) = -\nabla U_{att}(q) = \zeta(q_{goal}-q) \tag{3}$$

Following repulsive potential function can be used.

$$U_{rep}(q) = \begin{cases} \frac{1}{2} \eta \left(\frac{1}{\rho(q, q_{obs})} - \frac{1}{\rho_o} \right)^2 \\ \end{cases} \tag{4}$$

if

$$\rho(q, q_{obs}) < \rho_o$$

The negative gradient of the repulsive potential function:

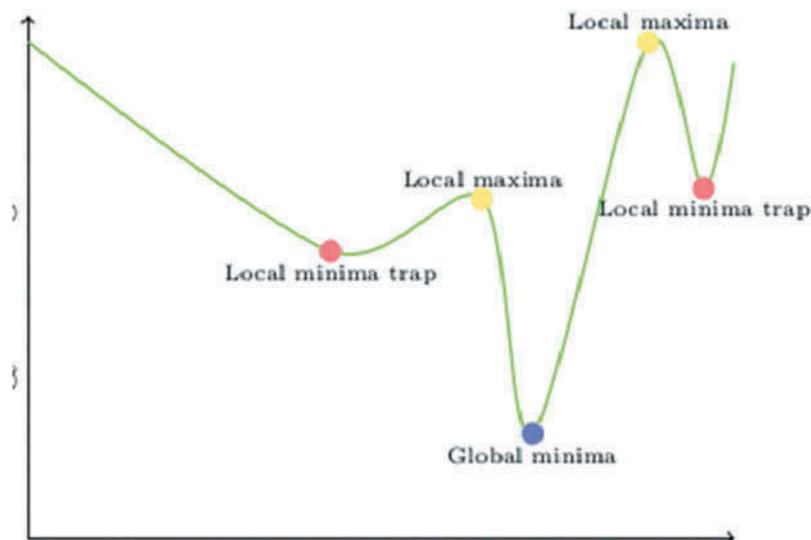
$$F_{rep}(q) = -\nabla U_{rep}(q) = \begin{cases} \zeta \left(-\frac{1}{\rho \left((q, q_{obs}) - \frac{1}{\rho_o} \right)} \frac{1}{\rho(q)^2} \frac{q - q_{obs}}{\rho(q)} \right) \\ \end{cases} \tag{5}$$

In potential field approach, an attractive field is created to reach the goal. The potential field is usually defined across the entire free space, and in each time step, potential field is calculated at the robot position, which calculates the induced force applied by the field. The robot then should move according to above-mentioned forces. The major problem with APF is that robot may trap in local/global minima problem, that is, the robot is stuck at point where both fields/forces cancel out the effect of each other and does not allow the robot to move further or even backward. As shown in Figure 2.

2.2. B. Dijkstra

The graph searching method is considered as the simplest method for finding a path for robot. It is considered as a well-defined, effective, and efficient method with less time and computational complexity in identifying a nonobstructive path. Environment is constructed for robot and the path is connected by line through robot easily reaches to target. The process continues until a better and optimal solution is achieved from one node to another. When the robot reaches the desired target, the robot is allowed to proceed to new location. Dijkstra algorithm is considered as graph searching method that solves the optimal path problem with non-negative edge path costs producing shortest path. It is used to find path cost from single point to single destination. This

Figure 2. Local and global minima in a system.



algorithm has great importance in traffic information system where tracking of source and destination can be done via tracking the source and destination.

It is used for determining the shortest distance with lower cost between the initial node and other nodes in a graph. The main crux of the algorithm is to repetitively calculate the shortest distance from a initial point to end point at the same time excluding longer distance path (Saleh Alija, 2015).

2.3. C. A star

A* is a search algorithm that can also be used to find path-finding. The algorithm continuously searches for unexplored location in graph. All the locations are searched in graph when the target location is reached, the algorithm stops. And if target is not achieved then it sets all the neighbors for exploration to search for the shortest path. A-star algorithm is the popular for path finding in games (Saleh Alija, 2015; Cui & Shi, 2011).

3. Local navigation methods

3.1. A. LIDAR

In local navigation techniques, sensors are usually employed to control the orientation and position of robot. For such use, LIDAR sensor is frequently used for automation purpose. LIDAR works independently as compared to GPS system; therefore, it has the capability of mapping the environment. LIDAR can be used independently but when coupled with other sensors like GPS, Inertial navigation system, and camera, it gives improved results.

For example, together with camera it provides powerful positioning tool. This system can be employed for mapping the local environment to locate and identify the landmarks position, which in general is called as SLAM (Simultaneous Localization and Mapping). With the help of this technique, mobile robot automatically corrects its position and orientation remotely. Motors encoder sensors employment with LIDAR can also improve and enhance accuracy.

3.2. B. Vector filed Histogram

Vector Field Histogram (VFH) is another local navigation method used to solve the path planning problem for mobile robots. The idea of VFH is based on VFF (Virtual Force Filed) method. As the name indicates its a field, so obstacles detected at a certain distance from vehicle will apply repulsive force on vehicle to move away from obstacles and to draw the vehicle toward goal point an attractive force is used. VFH uses a certainty grid-like radar screen, where obstacles found by sensor will count up sum certainty value at the corresponding coordinates in the certainty grid. Which means, higher the certainty value reveals that the real object is detected by sensor range. In real time, the grid is continuously updated at every instant hence this method is suitable for sparse moving objects.

3.3. C. Overview of navigation techniques and applications for autonomous guided vehicles

Similarly, Autonomous Guided Vehicle (AGV) system can also be classified into different categories as shown in Figure 3. The AGV can be categorized into two methods, depending upon the number of load units it can carry simultaneously, that is, Single Unit Load or Multiple Unit Load. A load is considered as single unit, which carries vehicle from its pick-up point to drop-off point. In single unit load system, an empty, idle vehicle is chosen for task to perform, that is, to deliver load to assigned destination. Then vehicle travels from its initial position to pick-up position to acquire the load and then travels back to its drop-off destination. During the load drop-off assignment task, the vehicle is not interrupted by any other task. In multiple unit load system, the loaded vehicles are interrupted during their ongoing task to pick up additional loads. By assigning vehicle to a different task, affects the load for ongoing task and the other additional load the vehicle will be carrying. Therefore, scheduling and planning function parameters be introduced in controller to determine vehicle assignment to carry load.

Figure 3. Division of different AGV system.



The path guidance for AGV can be classified as static path determination or dynamic path determination. For static path vehicle uses pre-defined path between its origin and destination point. As mentioned earlier in direct guidance system, embedded wire, magnetic tapes, radio-frequency identification (RFID) chips, and dead reckoning are used to guide vehicle. Static path can also be subdivided into two categories: unidirectional and bidirectional. In unidirectional system, vehicle is allowed to follow and travel in single direction whereas in bidirectional system, vehicles can navigate in any direction; this functionality is achieved by using turn-around points or bidirectional vehicles which can move forward or backward. In dynamic path system, vehicle behaves autonomously to determine path by detecting and avoiding obstacle. In this system, the vehicle knows its destination via some coordinates system. Internal navigation system is used by vehicle to reach its destination.

AGVs can also be classified as direct and indirect according to their addressing modes. The direct addressing mode is considered as city-taxi service, where destination of a person is served by vehicle. Similarly, in AGV the current status of system is used in planning function to give route to vehicle from its start position to destination position. Whereas in in-direct addressing system, the vehicle route may not include every station that comes its way. It means that the stations are divided such that there is subset of every station that AGV has to reach. AGV plans the route and uses station subset to reach its destination.

Brief description of Navigation guidance system is following. The system can be divided into Direct, Relative, and Absolute system depending upon the type of system being used, as shown in Figure 4.

1) *Wired Type*: Wired-type navigation uses a slot or wire which is cut and placed below the surface. A sensor is installed at the bottom of AGV which detects the position according to radio signal being transmitted to wire that information is used for steering circuit which helps AGV to follow path.

2) *Guide Type*: In Guide-type sensor vehicle follows the path of tape or painted line by the help of camera. The information is transferred via Radio communication. The advantage of guide path is that it can be relocated and removed anywhere.

Figure 4. Division of navigation system.

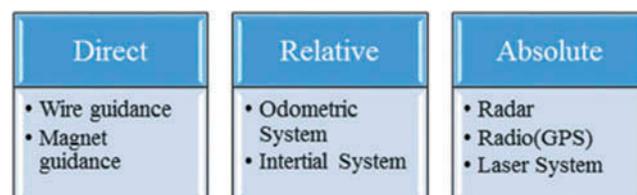
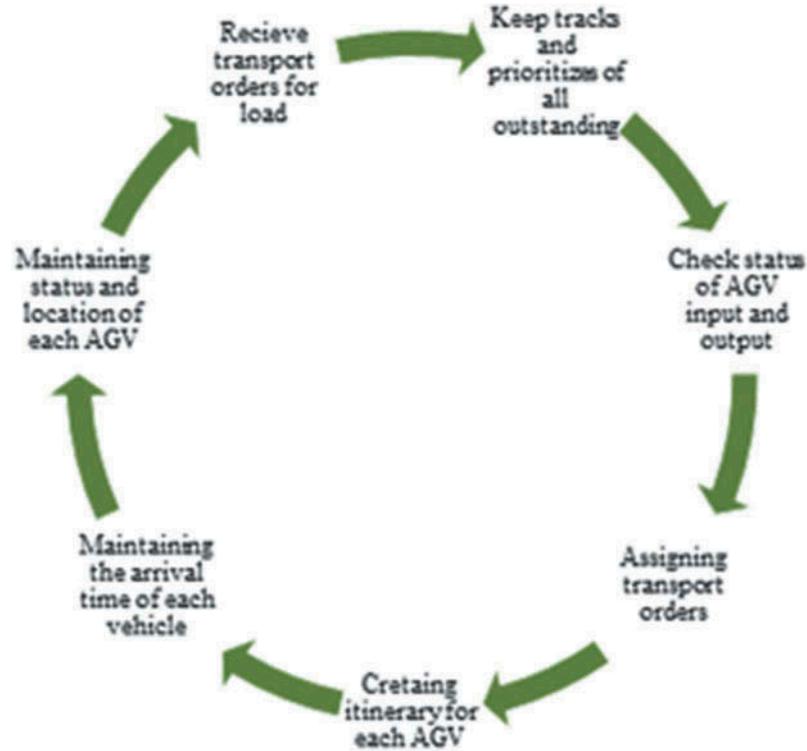


Figure 5. Tasks perform by controller.



3) *Laser Type*: Laser Navigation is considered to be the most effective and efficient technique for obstacle avoidance and path following. It does not require any wires, rails, and tracks for its motion. A beam is transmitted and received form sensor, the time taken by the beam to travel and come back helps is determining the distance and angle which helps vehicle in its motion. Then the current pose of AGV is compared with already installed map inside the memory of AGV.

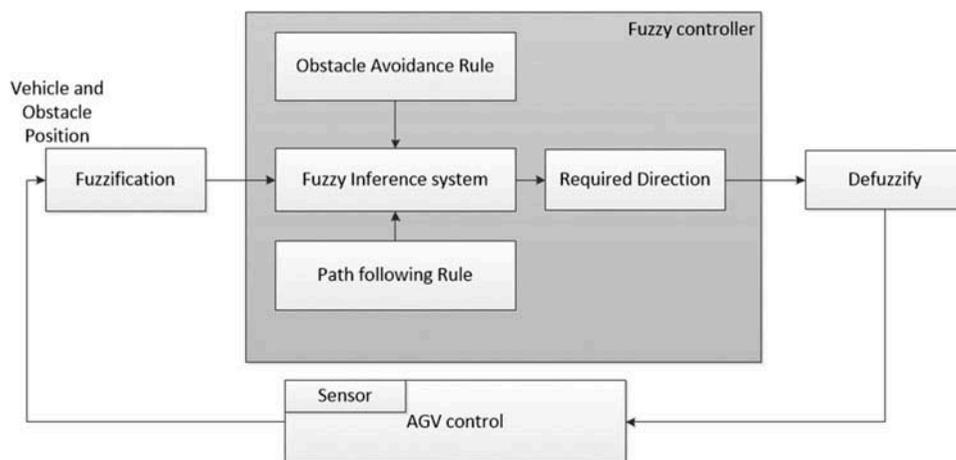
4) *Gyro based*: The navigation can be performed by the help of computer control system which assigns and directs tasks to vehicle. Transponders are used for this purpose, buried under the floor helps the vehicle to verify the vehicles position and orientation. Such navigation is performed through gyroscopic sensor. The combination laser sensor and gyroscopic measurements gives another method for range finding. It is highly efficient method for determining the shortest route for permitted path.

5) *Vision Based*: Vision-based AGVs use camera to acquire environment features and made decision based on those features to navigate the vehicle. On the other-hand Geo guidance understands its environment by the use of location. It uses fixed reference to identify any product within the warehouse and with this help, vehicle navigates itself. In automatic guided vehicle, the management of vehicle tasks also has vital importance. All the tasks are controlled by controller. The controller performs following tasks, as shown below in Figure 5.

3.4. D. Methods involve in navigation system

Fuzzy logic has significant importance in mobile robot and autonomous guided vehicle control. They are best employed for inaccurate and imprecise information in sensor measurement and heuristic based knowledge. They can be incorporated with AGV system to control the motion and steering of motor. As fuzzy logic works on rule-based system, different rules can be created to drive AGV. During the fuzzification process vehicle and obstacle position is obtained from sensors employed on AGV. Then obstacle avoidance and path following rule base are created which are then infused with fuzzy inference system to get the desired direction for AGV movement, as shown in Figure 6.

Figure 6. Functional block for fuzzy controller.



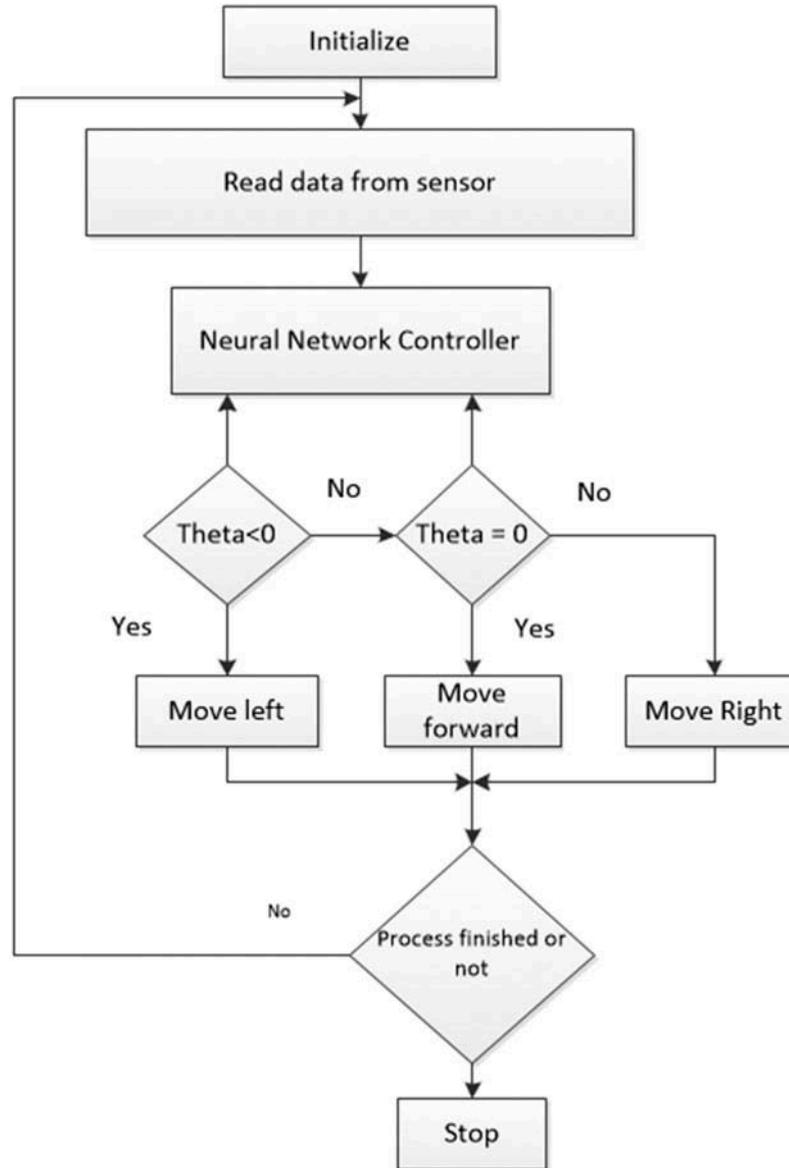
Similarly, NN can also be used for AGV system in similar manner. NN system relies on biological nervous system, like brain processes the information. It is made up of artificial neurons interconnecting one another working together to produce a specific output. Learning the biological system involves adjustment to highly interconnected synaptic connections existing between neuron, they adapt to the given data set. NNs have the tendency to learn from surrounding environment and are made to learn from experience to improve their efficiency also they are well suited for environments fluctuations. Figure 7 shows a simple block diagram of how NN can be used as controller. The data read from sensor is fed to NN controller to decide to take action based on the membership functions declared.

These different navigation methods are fused with fuzzy logic controller and NN to achieve better and highly efficient results in terms of Position and Orientation.

There are different line following techniques proposed by many researchers, for example, B. B. Abu Bakar et al. (Abu Bakar, Mohmad, & Adam, 2016) presented line following by the use of Sugeno Inference Method in which magnetic guide with 8 bit input line sensor were modified into a weighted number to determine the desired output. The weighted number are used as input to another fuzzy logic controller to get the accurate speed for line following robot. The use of different kind of sensor also helps in guiding the robot for obstacle avoidance and path following. Infrared sensor is used to estimate the position and to avoid the obstacle. Path following method also use wire guided techniques, in which current carrying wire is buried in floor then by the help ultrasonic sensor vehicle guides itself back on line once the obstacle is detected. The use of ultrasonic sensor is considered as less sophisticated method to avoid and detect obstacle (Cooke, 1983). Julliere et al. (Julliere, Marce, & Place, 1983) have proposed an obstacle avoidance method using fuzzy logic, using the input sensors separately. Li et al. (Li & Yang, 2003) Have used Fuzzy Logic for control and trajectory tracking of an autonomous unicycle robot. As per Oscar et al. (Castillo, Aguilar & Cárdenas, 2006), the use of fuzzy logic for controlling the educational mobile robot has been discussed to avoid obstacles. In (Surmann, Huser, & Peters, 1995) an autonomous robot that cope with approximate and uncertain information has to identify situations to maneuver in real time. The paper discusses a fuzzy-rule-based system approach for controlling the movement and actions of an autonomous robot. Controlling and guiding of the robot are acquired by combining global strategies and local actions within the fuzzy controller. Similarly, another fuzzy-control-based robot with obstacle avoidance algorithm is discussed in (Bento, Pires, & Nunes, 2002), in which robot is allowed to move in a planned path with the control of angle, distance, linear, and angular speed. The performance shows that fuzzy logic controller showed good behavior for avoidance of obstacle.

The research of Mustafa et al. (Mustafa, Ozdemirel Nur, & Sinan, 2000; Soylu, Özdemirel, & Kayaligil, 2000; Yang Simon & Max, 2000) shows a special type of AGV routing problem. For free ranging AGV, the

Figure 7. Block diagram of neural network controller.



problem highlighted is to locate the shortest path by the help of which it can carry out multiple number of P&D tasks. An Artificial Neural Network ANN algorithm was introduced based on Kohonen's self-organizing maps. Another paper (Surmann et al., 1995) discussed the mobile robot navigation problems and obstacle avoidance by the biological inspired NNs. In (Payne & Stern, 1985), authors have emphasized on the objective for creating a robot which navigates in unknown environment while performing necessary delivery tasks. The robot used sonar sensor and infrared sensor, the method of fusing two sensors together produced unreliable sensor data. For this purpose, the robot must have prior knowledge of environment or map of building to carry out process. Simple sensor fusion does not address these issues; thus Neural Network System was proposed to achieve the sensor fusion. NN proved that it delivers the reliable data.

3.5. E. Kinematics and dynamic analysis of mobile robot

In past decade, the control problem for autonomous vehicle has widely been researched and investigated thoroughly. In recent years, various soft computing techniques has been studied in

the development and design of autonomous mobile robot. In (Faisal, Hedjar, Al Sulaiman, & Al-Mutib, 2013), the authors have steered the mobile robot to goal point and avoiding obstacles via fuzzy logic approach. Wang and Yang (Wang & Yang, 2003) created the neuro fuzzy controller for nonholonomic differential drive robot for its navigation purpose. To read obstacle distance, four infrared sensors were used and their distance information is fed to controller for maintaining the speed of motors. Jia et al. (Jia, Yan, Fan, Li, & Gao, 2012) created a fuzzy controller for controlling smart tennis chair using omnidirectional wheels and pressure sensors. By the help of joystick device, wheelchair can be controlled in multiple ways.

Abdallah et al. (Abdallah & Dan, 2013) have created a fuzzy logic controller for searching target and path planning together with obstacle avoidance.

Xiong and Qu (Xiong & Shiru, 2010) elaborated a method for intelligent vehicles path tracking with two fuzzy controllers combining with vehicle control direction to assist drivers on highway and sometimes play the role of driver to reduce accidents. It uses CMOS sensor as path recognition device to draw a path of center-line through image processing.

Liang et al. (Liang, Xu, Wei, & Hu, 2010) have done the kinematic modelling for the two-wheeled differential drive robot. Martinez et al. (Martinez, Castillo, & Aguilar, 2009) have modelled the dynamics and kinematics trajectory tracking control for autonomous unicycle robot by the help of GA and type 2 fuzzy logic.

3.6. F. Soft computing techniques used for robot navigation

In past years, different soft computing techniques have been proposed by researcher to solve the obstacle avoidance problem and robot navigation in different environments.

1) *Fuzzy logic Technique*: The introduction of fuzzy set theory was first presented by Professor Lofti Zadeh, in 1965 at University of California (Montaner & Ramirez-Serrano, 1998; Zadeh, 1975). The fuzzy logic theory has widespread applications in the signal and information processing, control engineering, pattern recognition, decision-making, expert system, and so on. The system produces the efficient independent intelligent system. Fuzzy logic systems are naturally inspired by human reasoning, which works based on perception.

In Fuzzy logic, a crisp set of input values accumulate and together transform to a fuzzy set with a set of inference rules during a fuzzification step. After that, in defuzzification process the produced output gets transformed into a crisp set using membership function. Boubertakh et al. (Boubertakh, Tadjine, Gloennec, & Labiod, 2008) designed eight rule-based fuzzy controllers for path following and obstacle avoidance for mobile robot. In (Yousfi, Rekik, Jallouli, & Derbel, 2010), for obstacle avoidance and robot navigation purpose, the authors used Gradient method-based Takagi Sugeon fuzzy controller to tune different membership function parameters to acquire optimal result for navigation purpose. Figueiredo et al. (Figueiredo, Vellasco, & Pacheco, 2005) used Khepera simulator with agents to control robot. These agents are based on fuzzy logic. The sets of fuzzy rules are defined to control the behavior of every agent. The behavior includes the heading angle, position of robot and sensor value. The system was made efficient by including the memory system, which helps robot to look for alternative route when get trapped. A good control system should avoid dead end situation, and this method proves to be the successful. Lakehal et al. (Lakehall, Amirat, & Pontnau, 1995) presented a fuzzy logic controller for path following based on the orientation and position errors. They shown that controlling the two independently wheels give lateral and longitudinal control of vehicle. Omrane et al. (Omrane, Masmoudi, & Masmoudi, 2016) have designed and implemented the trajectory tracking control robot in an indoor environment by using the dc motor and infrared sensor for measuring distance to obstacles and encoders to adjust the speed and position.

Muthu et al. (Muthu, Thierry Gloude, Swaminathan, & Satish Kumar, 2012) studied the Atmega microcontroller-based fuzzy logic controller for mobile navigation. The controller was trained for

navigation in an unknown environment with human aid. The gets the obstacles distance as input from the sensors to control the motion of left and right motor. Moreover, the fuzzy logic controller for an indoor environment sensor-based mobile robot navigation has been discussed in (Li & Yang, 2003; Muthu et al., 2012). Li et al. (Li, Chang, & Tong, 2004b) use fuzzy logic for obstacle avoidance approach with visual landmark recognition. Li and Chang et al. (Li et al., 2004b) use two mobile robots for following the path and for tracking the moving target. A fuzzy controller together with the infrared sensors were used for tracking. Samsudin et al. (Samsudin, Ahmad, & Mashohor, 2011) have combined the GA and reinforcement learning method to optimize fuzzy controller. Beom and Cho (Beom & Cho, 1995) also presented the idea of fuzzy reinforcement by learning of sensor-based robot navigation. By the combination of fuzzy controller and GA, the path following and control problem of Autonomous Mobile Robot has been solved by use of ultrasonic range finder in (Rusu, Birou, & Szoke, 2010). Farooq et al. (Farooq, Hasan, Abbas, & Asad, 2011) did comparative study for Mamdani-type fuzzy logic and zero-order Takagi-Sugeno models for obstacle avoidance and robot navigation. The controllers receive obstacle distance as input from right and left ultrasonic sensor to control the motion of right and left motors. They presented the idea that Takagi-Sugeno fuzzy model uses less memory space for implementation in real-time microcontroller and on the other hand, Mamdani-type fuzzy model gives better result in terms of smoothness.

3.7. Hybridization of fuzzy logic and swarm algorithms

Algabri et al. (Algabri, Mathkour, Ramdane, & Alsulaiman, 2015) integrated the fuzzy logic technique with the soft computing techniques such NN, PSO, and GA to optimize the different membership functions parameters for enhancing the navigation performance of robot. They presented two fuzzy logic behaviors: Obstacle avoidance behavior (AFLC) and motion to target behavior (MFLC). In (Rusu et al., 2010), the authors have discussed the Fuzzy Pulse Width Modulation (PWM) controller. In (Hui & Pratihari, 2009), they have created genetic-neural and genetic-fuzzy controller for adaptive navigation path planning of mobile robot between dynamic obstacles. In their research, GA is used for adjusting the weight of NN and fuzzy membership functions. Selekwa et al. (Selekwa, Dunlap, Shi, & Collins, 2008) developed the fuzzy controller for robot navigation in deeply populated obstacle environment. The authors created two behavioral controllers namely goal-seeking and obstacle avoidance. Compass measurement technique is used for goal-seeking behavior and range finding sensor used for obstacle avoidance behavior. Pratihari et al. (Pratihari, Deb, & Ghosh, 1999) have presented the combination of genetic-fuzzy technique based on GA and fuzzy logic to solve the motion-planning problem of robot in dynamic environment. Abdessemed et al. (Abdessemed, Benmahammed, & Monacelli, 2004) have developed the evolutionary algorithm for optimization of antecedent and its consequent parameters of fuzzy logic controller, and implemented it for robot path following. Faisal et al. (Faisal et al., 2013) designed the sensor-based wireless fuzzy logic controller for robot navigation for industries between dynamic and static objects. Two different fuzzy logic controllers: obstacle avoidance fuzzy logic control (OAFLC) and tracking fuzzy logic control (TFLC) helps robot to find collision free path to reach its destination. Dongshu et al. (Dongshu, Yusheng, & Wenjie, 2011) presented the behavior-based fuzzy controller to solve navigation problem of robot in an unknown environment. Different fuzzy-rule-based controller helps the robot to get out of trapped situation and predict the behavior. Four different logic controllers are presented by Li et al. (Li, Chang, & Chen, 2003), that is, parallel parking fuzzy, garage parking fuzzy, corner control fuzzy, and wall following fuzzy for car-like-mobile robot (CLMR). The designed fuzzy logic controller was tested on FPGA for real time. Li and Chang (Li, Chang, & Tong, 2004a) have proposed the real-time fuzzy tracking control for target for mobile robots by use of infrared sensor. Ayari et al. (Ayari, Hadouaj, & Ghedira, 2010) have presented the intelligent multiagent fuzzy logic control system, which helps the robot to navigate on its own without human intervention in uncertain environment. By the help of fuzzy logic control Antonelli et al. (Antonelli, Chiaverini, & Fusco, 2007) have developed the path planning approach.

3.8. Neural network techniques for mobile robot navigation

As discussed by Zhang and Huang, the easiness of NNs and their tendency to do distributed processing extending their abilities for learning and generalization, have ranked them with

a popular methodology, which make popular in real-life applications (Zou, Hou, & Fu, 2006). Facial expressions, Hand written letters recognition, finding a shortest route for a travelling and defining a schedules for job-shop are some of the examples of problems which could only be solved by using NNs.

NN system relies on biological nervous system, like brain process the information. It is made up of artificial neurons interconnecting one another working together to produce a specific output. Learning the biological system involves adjustment to highly interconnected synaptic connections existing between neuron, they adapt to the given data set.

Zou et al. (Zou et al., 2006) presented the literature survey of NN and their applications in the field of robotics. For robust path planning authors in (Xiao, Liao, & Zhou, 2007) combined the technique of multilayer feed forward artificial NN with Q reinforcement method. By the use of Proportional Integral Derivative (PID) and Multilayer NN controller Rai and Rai (Rai & Rai, 2013) designed Arduino microcontroller-based DC motor for speed control. By using NN architecture Patino and Carelli (Patino & Carelli, 2004) designed automatic steering controller for autonomous mobile robot. Yang and Meng (Yang & Meng, 2001) developed collision-free path in dynamic environment by the use NN. Nicholas et al. (Nichols, McDaid, & Siddique, 2013) presented wall following robot which is biologically inspired NN dependent. Also online path following and planning for unknown obstacles is interesting problem in the field of robotics. Motlagh et al. (Motlagh, Nakhaeinia, Tang, Karasfi, & Khaksar, 2014) have proposed the obstacle avoidance and goal-seeking behaviors using NN. Hybrid NN for robot navigation has been addressed by Gavrilo and Lee (Gavrilo & Lee, 2007).

3.9. Integration of neural network and swarm algorithms

Rossomando and Soria (Rossomando & Soria, 2015) have solved the trajectory tracking problem for which they proposed the adaptive NN PID controller. Al-Jarrah et al. (Al-Jarrah, Shahzad, & Roth, 2015) have proposed the probabilistic neuro-fuzzy architecture which is a combination of Adaptive Neuro-Fuzzy Inference System (ANFIS) and first-order Sugeno fuzzy inference model, they used it for coordination of multiple robots and path planning. Authors uses the leader-follower method to control the robot orientation and position in environment. ANFIS is used for generating automatic rule from numerical data and fuzzy model is used to control angular and linear velocities of follower and leader robot. In (Janglova, 2004), authors have proposed the technique for NN for controlling and path following for robot. For path following and control purpose, two different NN controllers are applied. The first controller helps the robot to search for free path and second controller helps in avoiding obstacle in environment. Hopfield NN for obstacle avoidance and path planning in complex environment is presented by Glasius et al. (Glasius, Komoda, & Gielen, 1995). Chohra et al. (Chohra, Farah, & Benmehrez, 1998) designed intelligent navigation system for mobile robot by use of multilayered NN. The path following and localization problem for robot has been solved by using recurrent neural network (RNN) by Brahmi et al. (Brahmi, Ammar, & Alimi, 2013). This RNN helps the robot to autonomously navigate in an unknown environment. In (Kim & Chwa, 2015), the authors designed type-2 fuzzy neural network (IT2FNN) to solve the orientation stabilization and obstacle avoidance of wheeled robots. IT2FNN has three layers and four inputs: input, hidden, and output layer and distance between robot and closet obstacle, distance between robot and target point, obstacle angle and target angle, respectively. The outputs are: angular and linear velocities of robot. In (Yang, Hu, Yuan, Liu, & Meng, 2003), by the help of NN authors have proposed how to control the dynamic nonholonomic robot.

3.10. Hybridization of neuro-fuzzy techniques

Zhu and Yang (Zhu & Yang, 2007) proposed a reactive-based neuro-fuzzy navigation system for mobile robot. Two behaviors, that is, obstacle avoidance and goal seeking and 48 rules were designed by the help of this model. To set the parameters of membership functions, NN-based technique is used which reduces the navigation path distance from start to end position. Godjevac and Steele (Godjevac & Steele, 1999) solve the mobile robot path following problem by integrating

Radial basis function neural network (RBFNN) and Takagi-Sugeno-type controller. Where, NN tunes the parameters of membership function and fuzzy logic handle the uncertainty of environment. Al Mutib and Mattar (Al Mutib & Mattar, 2011) used eight ultrasonic range finder sensors for detecting obstacles by proposing the sensor-based navigation system using neuro-fuzzy architecture. In (Li, Ma, & Wahl, 1997), the authors integrated the neuro-fuzzy architecture with behavior-based architecture for robot navigation in an unknown environment. The NN is used for training robot to reach to target and fuzzy controller is used for controlling velocities of robot.

Kim et al. (Kim & Chwa, 2015) have proposed an obstacle avoidance method for the position stabilization of the wheeled mobile robot using interval type-2 fuzzy NN controller. Zhang et al. (Zhang, Beetner, Wunsch, Hemmelman, & Hasan, 2005) presented the RAM-based neuro-fuzzy approach for robot navigation. They used the NN to control the heading angle of robot during travelling and fuzzy logic controller to interpret the sensory information. Marichal et al. (Marichal, Acosta, Moreno, Mendez, & Rodrigo et al., 2001) have contributed to design a neuro-fuzzy sensor-actuator to control the steer of robot in an unknown environment. Ma et al. (Ma, Li, & Qiao, 2001) mixed soft computing techniques like NN and fuzzy inference system to improve the decision-making speed and learning of a robot in an unknown environment. Baturone et al. (Baturone, Gersnoviez, & Barriga, 2014) authors have designed an embedded neuro-fuzzy controller for navigation of mobile robot between different the obstacles. Imen et al. (Imen, Mohammad, & Shoorehdeli, 2011) have used the Adaptive Neuro-Fuzzy Inference System (ANFIS) technique to eradicate the path-tracking problem of the nonholonomic wheeled robots. Authors have adjusted the membership function parameters using gradient descent learning algorithm. In (Ganapathy, Yun, & Ng, 2009), authors designed the two controllers: Artificial Neural Network (ANN) for wall-following of robot and fuzzy logic controller for obstacle avoidance. The controllers get inputs from the different sensors to avoid the obstacles in view when the robot travels towards the desired target. Zhao and Wang (Zhao & Wang, 2012) have solved the navigation problem for autonomous robot by incorporated sonar sensors with the NN architecture.

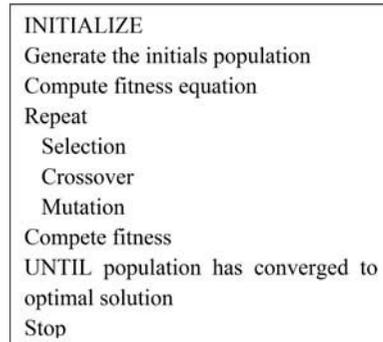
Algabri et al. (Algabri et al., 2015) have compared the Neuro-fuzzy, fuzzy logic, and PSO-fuzzy logic, artificial-intelligence algorithms for robot navigation system.

In (Lee & Chiu, 2009), to improve the path following of the robots, the authors developed a hybrid algorithm (GA with PSO) and Takagi-Sugeno-type recurrent neuro fuzzy system. Rusu and Petriu et al. (Rusu, Petriu, Whalen, Cornell, & Spoelder, 2003) have used contact sensors and infrared sensor for obstacle avoidance and target seeking; they have presented it by fusing a sensor-based neuro-fuzzy controller for mobile robot navigation. Al-Mayyahi et al. (Al-Mayyahi, Wang, & Birch, 2014) have used the Adaptive Neuro-fuzzy System (ANFIS) method for autonomous ground vehicle navigation. They designed a four ANFIS controllers for controlling the angular velocities, angle between robot and goal. In (Pradhan, Parhi, & Panda, 2006), authors proposed the neuro-fuzzy controller for navigational approach for multiple robots. The controller receives input, that is, obstacle distance from different sensors to drive the right and left wheel velocities of the robots. Algabri et al. (Algabri, Mathkour, & Ramdane, 2014) have studied same ANFIS controller and used for obstacle avoidance and robot navigation in a not-known environment. Khepera Simulator (KiKS) was used to perform different simulation tests.

6) *Genetic Algorithm*: The GA method is a process that drives biological evolution and it is used for solving optimization problems based on natural selection. The process starts with individual which fits best for population. The algorithm selects individuals at random from parent population having better fitness to produce children for next generation, which inherit parent's characteristics. By the help of this successive generation repetition, the population evolves moves toward an optimal solution and find the fittest individual. Pseudo code for GA is depicted in Figure 8:

Chaymaa et al. (Lamini, Benhlima, & Elbekri, 2018) have solved the path planning problem an improved crossover operator is suggested, for solving path planning problems using GAs in static environment.

Figure 8. Pseudo code for genetic algorithm.



Elshamli et al. (Elshamli, Abdullah, & Areibi, 2004) have solved the path planning problem in dynamic and static environment by using GA technique. Mohanta et al. (Mohanta, Parhi, & Patel, 2011) have optimized the navigation path length of robots in cluttered space by designing Petri-GA technique. Kubota et al. (Kubota, Morioka TKojima, & Fukuda, 2001) used fuzzy controller for guidance of robot in a dynamic and static environment, and the GAs were integrated with it for optimizing the navigation path length. In (Ming, Zailin, & Shuzi, 1996), to control the steering angle of robot in partially unknown environment, a GA has been designed to choose the best membership function parameters from fuzzy inference system. Hu et al. (Hu, Yang, Xu, & Meng, 2004) tried to develop the knowledge-based algorithm for navigation between maze and U-shaped environment.

Liu et al. (Liu, Lu, & Xie, 2006) used GA and fuzzy logic for finding the optimal path. Qu et al. (Qu, Xing, & Alexander, 2013) tried to develop the improved GA over a conventional GA for path planning of the multiple robots. The improved GA has capability of guiding the robots efficiently and effectively from the starting position to end position without causing any collision in the environment. In (Algabri, Mathkour, Hedjar, Alsulaiman, & Al Mutib, 2014), the authors implemented Genetic-Fuzzy Controller (GA-FLC) for optimizing and tuning the Gaussian membership function parameters for motion control. Castillo et al. (Castillo, Trujillo, & Melin, 2007) designed Multiple Objective Genetic Algorithm (MOGA) for path optimization of the robot. Arora et al. (Arora, Gigras, & Arora, 2014) have studied and presented the single fitness-based GA to avoid navigation problems in the dynamic environment. Fitness function was designed on the Euclidean distance formula between obstacle and robot.

7) *Particle Swarm Optimization Algorithm*: PSO is a computational method, population-based stochastic optimization algorithm, which is inspired by the social behavior of fish schooling or bird flocks. It was developed by J. Kennedy and R.C. Eberhard in 1995. PSO algorithm uses fitness function to find optimal or near optimal solutions of the problem. It consists of particles and each particle has velocity v_i and position x_i . Each particle adjusts its traveling speed according to corresponding flying experiences of its colleagues and itself. Every particle adjust and modifies its position according to current position, current velocity, and the distance between current

Figure 9. Diagram for sample particle in PSO.

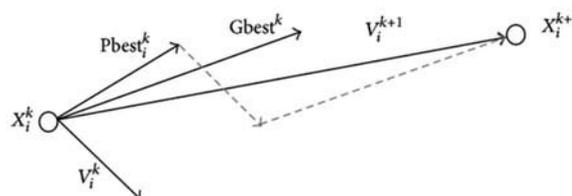
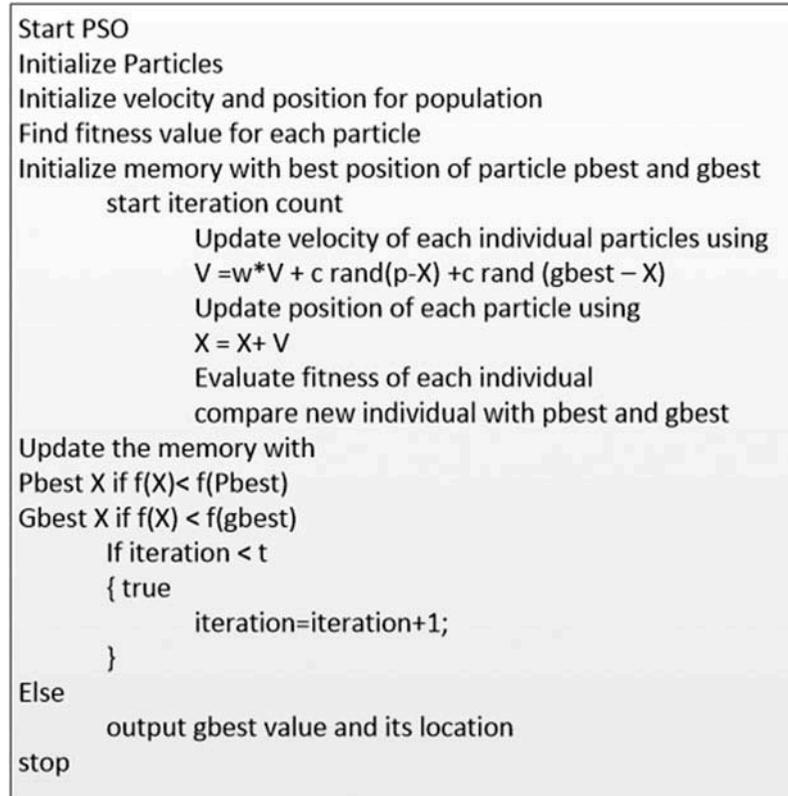


Figure 10. PSO algorithm.



position, P_{best} and G_{best} . A simple diagram for sample particle in PSO is shown in Figure 9 and a brief algorithm is shown how PSO algorithm works in Figure 10.

To update the velocities of every particle equation used is:

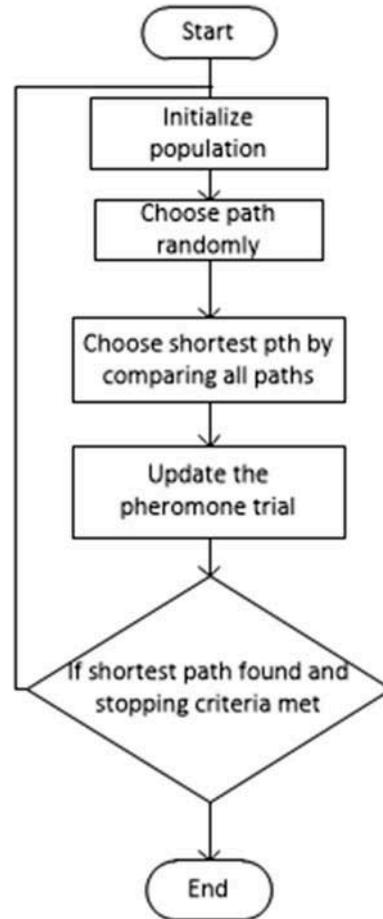
$$V_{t+1} = wV_t + crand(p_{best} - X_t) + crand(g_{best} - X_t)$$

where V_t = velocity of particle, X_t = position of particle, p_{best} = best position in individual, g_{best} = best position in group, c = constant, $rand$ = random variable

where $f(X)$ = objective function to be minimized

Ahmadzadeh and Ghanavati (Ahmadzadeh & Ghanavati, 2012) have presented the PSO algorithm-based navigation method for multiple robots. The robots move to the global best position of a particle in every iteration it takes. Zhang and Li (Zhang & Li, 2007) have proposed the new objective function for robot navigation by using PSO. This objective function works on the target and position of the obstacles in the environment. Masehian and Sedighzadeh (Masehian & Sedighzadeh, 2010) by using multi-objective PSO the authors have solved the motion planning problem of robot. Wong et al. (Wong, Wang, & Li, 2008) designed PSO-based optimal fuzzy controller to determine the velocities of the right motor and left motor of the differential drive robot. Huang (Huang, 2014) designed the Parallel Meta heuristic Particle Swarm Optimization (PPSO) algorithm for solving the global path planning problem of robot. The author also implemented the PPSO algorithm in field-programmable gate array (FPGA) chip for real time application. Juang and Chang (Juang & Chang, 2011) have proposed an evolutionary-group-based particle-swarm-optimization (EGPSO) for automatic learning of fuzzy system for wall following control and robot navigation. In (Lu & Gong, 2008), the authors have designed fitness function depending on target and obstacle in environment to overcome the path planning problem by minimization of problem.

Figure 11. A flow chart for pseudocode of ACO.



Allawi and Abdalla (Allawi & Abdalla, 2014) used PSO algorithm for determining the rules for fuzzy type-2 controller and input/output membership function parameters by proposing the sensor-based PSO-fuzzy type-2 model for the navigation purpose.

3.11. Ant colony optimization algorithm

ACO is another GA inspired by biological system of an ant's natural behavior. They use pheromones to find the shortest path between source and target. They deposit pheromones on ground to leave trail for other ants than other ants follow that path to reach target. A pseudocode for ACO algorithm is shown in Figure 11:

The ACO algorithm is mainly used for obstacle avoidance and navigation in the different environments. Contreras et al. (Contreras-Cruz, Ayala-Ramirez, & Hernandez-Belmonte, 2015) proposed ACO with evolutionary algorithm for solving the path-planning problem for mobile robot. The authors proposed the safest, smoothest, and collision-free path for mobile robot in obstacle-cluttered environment. Guan-Zheng et al. (Guan-Zheng, Huan, & Sloman, 2007) solved the path planning for robot by implementing Dijkstra algorithm and Ant Colony System (ACS) algorithm. Purian and Sadeghian (Purian & Sadeghian, 2013), studied fuzzy controller and ACO algorithm to solve the optimal path for robot in an unknown dynamic environment. The ACO algorithm finds the most-appropriate value from the fuzzy logic table and reduces the path length between the starting position and goal position of robot with obstacle avoidance capability. In (Ganapathy, Jie, & Parasuraman, 2010), by using ACO algorithm the authors have discussed numerous behaviors such as target-chasing, obstacle avoidance, and wall-following for robot

navigation. Meier et al. (Meier, Tullumi, Stauffer, Dornberger, & Hanne, 2017) proposed a novel Backup Path Planning Approach (BPPA) by reusing the scattered pheromones of ACO algorithm. The authors proposed the strategy which derive feasible path solely from available pheromone concentration.

Bi et al. (Bi, Yimin, & Yisan, 2009) studied how to improve the path-searching speed of robot in an environment by applying Ant Colony System (ACS). Search for optimal path for robot among irregular obstacle an improved intensified ACO is presented by Fan et al. (Fan, Luo, Yi, Yang, & Zhang, 2003). Sariff and Buniyamin (Sariff & Buniyamin, 2009) did the comparison performance between ACO and GA for path planning of robot in static environment and showed that the ACO utilizes lesser time for search of a shorter path in comparison of GA. Huang (Huang, 2011) presented an optimal kinematic controller based on the hybridization of GA and ACO algorithms for four-wheeled omnidirectional robots. The parameters of kinematics controller are obtained by minimizing the performance index using the proposed GA-ACO hybrid algorithm. GA has been combined with ACO in evolving new solutions by applying crossover and mutation operators on solutions constructed by ants. These optimal parameters are used in the GA-ACO kinematic controller to obtain better performance for four-wheeled omnidirectional mobile robots to achieve both trajectory tracking and stabilization.

Gracia et al. (Garcia et al., 2009) have used the ACO algorithm along with the Fuzzy inference system to solve the problem for path planning. The method was named as SACOdm (Simple Ant Colony Optimization, d = distance and m = memory).The authors have added the feature for remembering the visited nodes by ant and the decision making process was based on the distance between source and target where the optimal path criteria was tuned by Fuzzy inference System. In (Juang, Lai, & Zeng, 2015), two robots (a leader and a follower) were presented for navigation purpose by using fuzzy controllers (FC). They used continuous particle swarm optimization (AF-CACPSO) and ACO to avoid boundary obstacles. Liu et al. (Liu, Yang, Liu, Tian, & Gao, 2017) have used ACO algorithm to speed up the convergence speed. They used pheromone diffusion and geometric local optimization technique to enhance the optimal path. The path diffuses into the direction of potential filed force during search process, in this way ants tends to search the higher fitness space leaving the smaller search space for test pattern. Firstly the path is optimized by ant colony algorithm, further the algorithm is optimized by geometric algorithm.

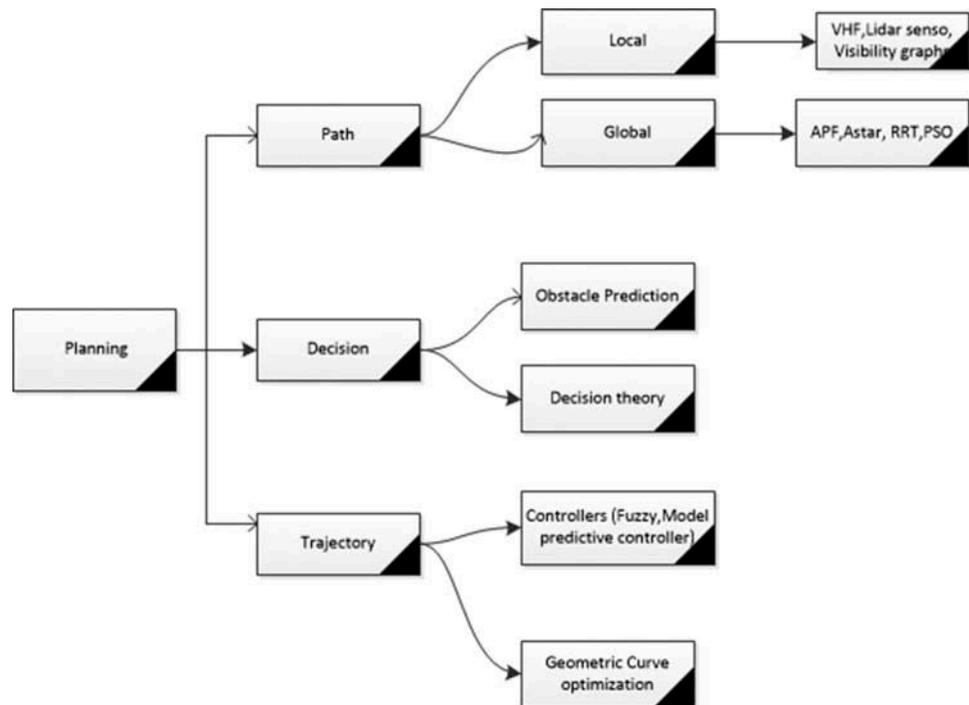
In (Luo & Chang, 2012), a review paper has been written for multisensor fusion and their application in the field of Mechatronic. Akka et al. (Akka & Khaber, 2018) improved the ACO algorithm that uses simulating probability which helps ants in their selection of next grid and employ heuristics information based on unlimited step length to expand the vision filed. The authors also improved the algorithm by adjusting the evaporation rate to help in convergence speed and expanding the search area.

Moreover, automation is considered as the outcome of series of processes, which gathers information from environment to do data processing and use that data to control the vehicle.

4. Results and discussion

A total of one 133 articles were reviewed in this study, covering a sufficient depth related to path planning. A survey was conducted between most-popular techniques involved in robot path planning and it has been seen that now researchers are working on reducing time and computational complexities. Path planning involves a lot of factors to be considered for producing the best possible results such as path length, stability, efficiency, and safety of vehicle is the most important of all. In the beginning authors have worked with single algorithm to reduce complexities, but it has been seen and experienced that no single algorithm presents the best of required features. The best performance requires the hybridization of algorithms that have best combination of robustness, response time, precision, and how much efficiently and intelligently the system responds to errors produced in algorithms. However, hybrid

Figure 12. Classification tree for path planning.



systems do not guarantee the best result and performance, hence a trade off needs to be found for any algorithm on which factors would be most suitable and appropriate. The researchers are still looking for balance which will give the best overall performance. Figure 12 shows the classification of path planning.

5. Conclusion

A comparison of deterministic and nondeterministic techniques has been shown in Table 1. The performance of particular technique depends on many factors, whereas table serves an indistinct guide for their performance.

From the research, different key factors are determined:

- (1) The researchers have mostly used soft computing techniques as compared to hard computing, that is, Deterministic, Non-deterministic, and Evolutionary Algorithms for robot navigation and obstacle avoidance.
- (2) Nature-inspired algorithms for obstacle avoidance and robot navigation has a lot more importance in research area and the hybridization of deterministic with Non-deterministic Algorithm is the upcoming choice for many researchers.
- (3) The researchers have used these techniques for static environment not for dynamic environment and did not implement on physical robots rather use simulations for their results.
- (4) It has been seen that for dynamic motion planning heuristic approaches tends to demonstrate better result

6. Strengths and weakness of hybrid algorithms

A conclusion has been drawn that hybrid methods are most popular when more than one objective is need to achieve. They involve integration of multiple methods, by taking maximum advantage from these methods and minimizing their drawbacks. For instance, integrating different methods

Table 1. Comparison of deterministic and nondeterministic techniques

Sr. No.	Soft Computing	Robust	Response	Precision	Intelligent	Computational Complexity	Time Complexity
1	Fuzzy logic	Average	Average	Low	Average	High	High
2	Neural Network	High	Average	High	High	High	High
3	PSO	Average	High	Average	High	Average	Average
4	GA	High	High	Average	Average	Average	Average
5	ACO	Average	Average	High	Average	High	High

Table 2. Summary of strengths and challenges of swarm algorithm (nature inspire algorithms)

Algorithms	Strengths	Challenges
Fuzzy logic	(a) Effective when integrated with other algorithms (b) can imitate control logic as human being	(a) Difficult to create rules for membership functions in a unstructured environment
Neural Network	(a) Real-time experiment and Simulations can be done (b) Gives great help in tuning membership functions (c) Helps in providing generalization and learning capabilities	(a) Difficult to handle number of buried layers in neuron system (b) Increasing number of layers may increase the computational complexity (c) Slow convergence speed
Particle Swarm Optimization	(a) Provide good result in simulations (b) It does not easily trap into local minima problem (c) It easy to implement because it does not have computational complexity (d) Quite faster than Fuzzy logic because of fast convergence	(a) In complex map, it is easy to get trap in local minima problem (b) Performance analysis is difficult due to objects are considered in polygon form
Genetic Algorithm	(a) Results are produced in simulation (b) Good optimization capability (c) Gives good result when integrated with different algorithm due to its easiness in implementation	(a) Difficult to handle in complex situations (Dynamic environment) (b) Can cause oscillations in system due to local minima problem
Ant Colony Optimization	(a) Produce good results in simulations (b) Easy to algorithm and easy to implement (c) Require less control parameters (d) Combine well with different other algorithm	(a) Slow convergence

can reduce noise, computational and time complexity, uncertainty in data, and local minima problem in APF method (Al-Mutib et al., 2016; Baklouti, John, & Alimi, 2012).

Though it seems that hybrid methods can help in achieving multiple objectives with lesser cost but these methods also have compatibility challenges. For example, not every method is compatible with everyone. Incompatibility of methods may result in producing worse results as compared to using single method. New problems and challenges may emerge due to the integration of two methods. This can also lead to unsatisfactory results, uncertainty in control performance and oscillations. Table 2 summarizes the strengths and challenges of different algorithm.

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References

Abdallah, K. B., & Dan, Z. Q. (2013). A fuzzy logic behavior architecture controller for a mobile robot path planning in multi-obstacles environment. *Research Journal of Applied Sciences, Engineering and Technology*, 5(14), 3835–3842.
 Abdessemed, F., Benmahammed, K., & Monacelli, E. (2004). A fuzzy-based reactive controller for a non-holonomic mobile robot. *ELSEVIER Robotics and*

- Autonomous Systems*, 47(1), 31–46. doi:10.1016/j.robot.2004.02.006
- Abu Bakar, B. B., Mohamad, S. S., & Adam, I. (2016). Navigation of an automated guided vehicle based on Sugeno inference engine. *Journal of Applied Sciences*, 16, 570–579. doi:10.3923/jas.2016.570.579
- Aghababa, M. P. (2012). “3D path planning for underwater vehicles using five evolutionary optimization algorithms avoiding static and energetic obstacles. *Applied Ocean Research*, 38, 48–62. doi:10.1016/j.apor.2012.06.002
- Ahmadzadeh, S., & Ghanavati, M. (2012). Navigation of mobile robot using the PSO particle swarm optimization. *Journal of Academic and Applied Studies (JAAS)*, 2(1), 32–38.
- Akka, K., & Khater, F. (2018). Mobile robot path planning using an improved ant colony optimization. *International Journal of Advanced Robotic Systems*.
- Al Mutib, K., & Mattar, E. (2011). Neuro-fuzzy controlled autonomous mobile robotics system. IEEE 13th International Conference on Modelling and Simulation, UK, p. 1–7.
- Algabri, M., Mathkour, H., Hedjar, R., Alsulaiman, M., & Al Mutib, K. (2014). Self-learning mobile robot navigation in unknown environment using evolutionary learning. *Journal of Universal Computer Science*, 20(10), 1459–1468.
- Algabri, M., Mathkour, H., & Ramdane, H. (2014). Mobile robot navigation and obstacle-avoidance using ANFIS in unknown environment. *International Journal of Computer Applications*, 91(14), 36–41. doi:10.5120/15952-5400
- Algabri, M., Mathkour, H., Ramdane, H., & Alsulaiman, M. (2015). Comparative study of soft computing techniques for mobile robot navigation in an unknown environment. *Computers in Human Behavior*, 50, 42–56. doi:10.1016/j.chb.2015.03.062
- Al-Jarrah, R., Shahzad, A., & Roth, H. (2015). Path planning and motion coordination for multi-robots system using probabilistic neuro-fuzzy. *ELSEVIER IFAC-Papers Online*, 48(10), 46–51. doi:10.1016/j.ifacol.2015.08.106
- Allawi, Z. T., & Abdalla, T. Y. A. (2014). PSO-optimized type-2 fuzzy logic controller for navigation of multiple mobile robots. IEEE International Conference on Methods and Models in Automation and Robotics (MMAR), Poland, p. 33–39.
- Al-Mayyahi, A., Wang, W., & Birch, P. (2014). Adaptive neuro-fuzzy technique for autonomous ground vehicle navigation. *Robotics*, 3(4), 349–370. doi:10.3390/robotics3040349
- Al-Mutib, K., Abdessemed, F., Faisal, M., Ramdane, H., Alsulaiman, M., & Bencherif, M. (2016, September). Obstacle avoidance using wall-following strategy for indoor mobile robots. In 2016 2nd IEEE International Symposium on Robotics and Manufacturing Automation (ROMA) (pp. 1–6). Ipoh, Perak: IEEE.
- AL-Nayar, M. M., Dagher, K. E., & Hadi, E. A. (2019). A comparative study for wheeled mobile robot path planning based on modified intelligent algorithms. *The Iraqi Journal for Mechanical and Materials Engineering*, 19(1), 60–74.
- Antonelli, G., Chiaverini, S., & Fusco, G. (2007). A fuzzy-logic-based approach for mobile robot path tracking. *IEEE Transactions on Fuzzy Systems*, 15(2), 211–221. doi:10.1109/TFUZZ.2006.879998
- Arora, T., Gigras, Y., & Arora, V. (2014). Robotic path planning using genetic algorithm in dynamic environment. *International Journal of Computer Application*, 89(11), 8–12. doi:10.5120/15674-4422
- Ayari, E., Hadouaj, S., & Ghedira, K. (2010). A fuzzy logic method for autonomous robot navigation in dynamic and uncertain environment composed with complex traps. IEEE 5th International Multi-conference on Computing in the Global Information Technology (pp. 18–23). Valencia, Spain.
- Baklouti, N., John, R., & Alimi, A. M. (2012). Interval type-2 fuzzy logic control of mobile robots. *Journal of Intelligent Learning Systems and Applications*, 4(04), 291. doi:10.4236/jilsa.2012.44031
- Baturone, I., Gersnoviez, A., & Barriga, A. (2014). Neuro-fuzzy techniques to optimize an FPGA embedded controller for robot navigation. In *ELSEVIER Applied Soft Computing 21* (pp. 95–106). Appl. Soft Comput.
- Bento, L. C., Pires, G., & Nunes, U., A behaviour based fuzzy control architecture for path tracking and obstacle avoidance, Proceedings of the 5th Portuguese Conference on Automatic Control (Controlo 2002), Aveiro, 2002, pp 341–346.
- Beom, H. R., & Cho, K. S. (1995). A sensor-based navigation for a mobile robot using fuzzy logic and reinforcement learning. *IEEE Transactions on Systems, Man, and Cybernetics*, 25(3), 464–477. doi:10.1109/21.364859
- Bi, Z., Yimin, Y., & Yisan, X. (2009). Mobile robot navigation in unknown dynamic environment based on ant colony algorithm. In IEEE WRI Global Congress on Intelligent Systems, (pp. 98–102). doi:10.1007/s12177-009-9034-6
- Boubertakh, H., Tadjine, M., Glorennec, P., & Labiod, S. (2008). A simple goal seeking navigation method for a mobile robot using human sense. Fuzzy logic and reinforcement learning. *Journal of Automatic Control*, 18(1), 23–27. doi:10.2298/JAC0801023B
- Brahmi, H., Ammar, B., & Alimi, A. M. (2013). Intelligent path planning algorithm for autonomous robot based on recurrent neural networks. IEEE International Conference on Advanced Logistics and Transport (ICALT) (pp. 199–204). Tunisia.
- Castillo, O., Aguilar, L. T., & Cárdenas, S. (2006). Fuzzy logic tracking control for unicycle mobile robots. *Engineering Letters*, 13(3), 73–82.
- Castillo, O., Trujillo, L., & Melin, P. (2007). Multiple objective genetic algorithms for path-planning optimization in autonomous mobile robots. *SPRINGER Soft Computing*, 11(3), 269–279. doi:10.1007/s00500-006-0068-4
- Chohra, A., Farah, A., & Benmehrez, C. (1998). Neural navigation approach for Intelligent autonomous vehicles (IAV) in partially structured environments. *Applied Intelligence*, 8(3), 219–233. doi:10.1023/A:1008216400353
- Choset, H. M. (2005). *Principles of robot motion: Theory, algorithms, and implementations*. MIT Press.
- Contreras-Cruz, M. A., Ayala-Ramirez, V., & Hernandez-Belmonte, U. H. (2015). Mobile robot path planning using artificial bee colony and evolutionary programming. *Applied Soft Computing*, 30, 319–328. doi:10.1016/j.asoc.2015.01.067
- Cooke, R. A. (1983). Microcomputer control of free ranging robots. *Proceedings of 13th International Symposium Industry Robots Robot*, 7, 2, 109–120.
- Cui, X., & Shi, H. (2011). A*-based pathfinding in modern computer games. *International Journal of Computer Science and Network Security*, 11(1), 125–130.
- Dongshu, W., Yusheng, Z., & Wenjie, S. (2011). Behavior-based hierarchical fuzzy control for mobile robot navigation in dynamic environment. IEEE International Conference on Control and Decision Conference (CCDC) (pp. 2419–2424). Mianyang, China.

- Elshamli, A., Abdullah, H. A., & Areibi, S. (2004) Genetic algorithm for dynamic path planning. In IEEE International Conference on Electrical and Computer Engineering (pp. 677–680). Canada.
- Engedy, I., & Horvath, G. (2010) Artificial neural network based local motion planning of a wheeled mobile robot. In IEEE International Symposium on Computational Intelligence and Informatics (CINTI), Hungary, pp. 213–218.
- Faisal, M., Hedjar, R., Al Sulaiman, M., & Al-Mutib, K. (2013). Fuzzy logic navigation and obstacle avoidance by a mobile robot in an unknown dynamic environment. *INTECH International Journal of Advanced Robotic Systems*, 10(1), 1–7.
- Fan, X., Luo, X., Yi, S., Yang, S., & Zhang, H. (2003) Optimal path planning for mobile robots based on intensified ant colony optimization algorithm. IEEE International Conference on Robotics, Intelligent Systems and Signal Processing (pp. 131–136). China.
- Farooq, U., Hasan, K. M., Abbas, G., & Asad, M. U. (2011) Comparative analysis of zero order Sugeno and Mamdani fuzzy logic controllers for obstacle avoidance behavior in mobile robot navigation. IEEE International Workshop on Current Trends in Information Technology (CTIT) (pp. 113–119). doi:10.1007/s10653-010-9355-1
- Figueiredo, K., Vellasco, M., & Pacheco, M. A. (2005). Hierarchical neuro-fuzzy models based on reinforcement learning for intelligent agents. In *International Work-Conference on Artificial Neural Networks* (pp. 424–432). Berlin, Heidelberg: Springer.
- Ganapathy, V., Jie, T. T. J., & Parasuraman, S. (2010) Improved Ant Colony Optimization for Robot Navigation. IEEE International Symposium on Mechatronics and its Applications (ISMA) (pp. 1–6). Sharjah, United Arab Emirates.
- Ganapathy, V., Yun, S. C., & Ng, J. (2009) Fuzzy and neural controllers for acute obstacle avoidance in mobile robot navigation. IEEE/ASME International Conference on Advanced Intelligent Mechatronics (pp. 1236–1241). Singapore.
- Garcia, M. P., Montiel, O., Castillo, O., Sepulveda, R., & Melin, P. (2009). Path planning for autonomous mobile robot navigation with ant colony optimization and fuzzy cost function evaluation. *Applied Soft Computing*, 9(3), 1102–1110. doi:10.1016/j.asoc.2009.02.014
- Gavrilov, A. V., & Lee, S. (2007) An architecture of hybrid neural network based navigation system for mobile robot. IEEE Seventh International Conference on Intelligent Systems Design and Applications (pp. 587–590). Brazil. doi:10.1007/s00101-007-1152-6
- Ghorbani, A., Shiry, S., & Nodehi, A. (2009) Using genetic algorithm for a mobile robot path planning. In IEEE International Conference on Future Computer and Communication (pp. 164–166). Malaysia.
- Glasius, R., Komoda, A., & Gielen, S. C. (1995). Neural network dynamics for path planning and obstacle avoidance. *Neural Networks*, 8(1), 125–133. doi:10.1016/0893-6080(94)E0045-M
- Godjevac, J., & Steele, N. (1999). Neuro-fuzzy control of a mobile robot. *Elsevier Neurocomputing*, 28(1), 127–143. doi:10.1016/S0925-2312(98)00119-2
- Gomez, E. J., Martinez Santa, F., & Martinez Sarmiento, F. H. A. (2013) Comparative study of geometric path planning methods for a mobile robot: Potential field and voronoi diagrams. In IEEE International Congress of Engineering Mechatronic and Automation (CIIMA), Colombia, pp. 1–6.
- Guan-Zheng, T. A. N., Huan, H., & Sloman, A. (2007). Ant colony system algorithm for real-time globally optimal path planning of mobile robots. *Acta Automatica Sinica*, 33 (3), 279–285.
- Hassani, I., Maalej, I., & Rekek, C. (2018). Robot path planning with avoiding obstacles in known environment using free segments and turning points algorithm. *Mathematical Problems in Engineering*. doi:10.1155/2018/2163278
- Hu, Y., Yang, S. X., Xu, L. Z., & Meng, M. Q. (2004) A knowledge based genetic algorithm for path planning in unstructured mobile robot environments. IEEE International Conference on Robotics and Biomimetics (ROBIO) (pp. 767–772). China.
- Huang, H. C. (2011, May). Design of optimal kinematic controller based on GA-ACO hybrid algorithm for four-wheeled omnidirectional mobile robots. In 2011 8th Asian Control Conference (ASCC) (pp. 902–907). Kaohsiung: IEEE.
- Huang, H. C. (2014). FPGA-based parallel metaheuristic PSO algorithm and its application to global path planning for autonomous robot navigation. *Journal of Intelligent & Robotic Systems*, 76(3–4), 475–488. doi:10.1007/s10846-013-9884-9
- Hui, N. B., & Pratihari, D. K. (2009). A comparative study on some navigation schemes of a real robot tackling moving obstacles. *Robotics and Computer-Integrated Manufacturing*, 25(4), 810–828. doi:10.1016/j.rcim.2008.12.003
- Ibraheem, I. K., & Ajeil, F. H. (2018). Multi-objective path planning of an autonomous mobile robot in static and dynamic environments using a hybrid PSO-MFB optimisation algorithm. arXiv preprint arXiv. *Cornell University, Computer science, Robotics*, 1805, 00224.
- Imen, M., Mohammad, M., & Shoorehdeli, M. A. (2011) Tracking control of mobile robot using ANFIS. IEEE International Conference on Mechatronics and Automation (pp. 422–427). China.
- Janglova, D. (2004). Neural networks in mobile robot motion. *International Journal of Advanced Robotic Systems*, 1(1), 15–22. doi:10.5772/5615
- Jia, S., Yan, J., Fan, J., Li, X., & Gao, L., “Multimodal intelligent wheelchair control based on fuzzy algorithm,” in Proceedings of the IEEE International Conference on Information and Automation (ICIA '12) (pp. 582–587). Shenyang, China, June 2012. doi:10.1094/PDIS-11-11-0999-PDN
- Juang, C. F., & Chang, Y. C. (2011). Evolutionary-group-based particle-swarm optimized fuzzy controller with application to mobile-robot navigation in unknown environments. *IEEE Transactions on Fuzzy Systems*, 19(2), 379. doi:10.1109/TFUZZ.2011.2104364
- Juang, C. F., Lai, M. G., & Zeng, W. T. (2015). Evolutionary fuzzy control and navigation for two wheeled robots cooperatively carrying an object in unknown environments. *IEEE Transactions on Cybernetics*, 45 (9), 1731–1743. doi:10.1109/TCYB.2014.2359966
- Julliere, M., Place, H., Bazin, E. et al. (1988). A guidance system for a mobile robot. *Journal of Intelligent and Robotic Systems*, 1, 243. doi: 10.1007/BF00238768.
- Kim, C. J., & Chwa, D. (2015). Obstacle avoidance method for wheeled mobile robots using interval type-2 fuzzy neural network. *IEEE Transactions on Fuzzy Systems*, 23(3), 677–687. doi:10.1109/TFUZZ.2014.2321771
- Kubota, N., Morioka TKojima, F., & Fukuda, T. (2001). Learning of mobile robots using perception-based genetic algorithm. *ELSEVIER Measurement*, 29(3), 237–248. doi:10.1016/S0263-2241(00)00044-0
- Lakehall, B., Amirat, Y., & Pontnau, J., Fuzzy Steering Control of a Mobile Robot, (1995), Industrial Automation and Control, Emerging Technologies, International IEEE/IAS (pp. 383–386). Taipei, Taiwan.

- Lamini, C., Benhlima, S., & Elbekri, A. (2018). Genetic algorithm based approach for autonomous mobile robot path planning. *Procedia Computer Science*, 127, 180–189. doi:10.1016/j.procs.2018.01.113
- Lee, C. H., & Chiu, M. H. (2009). Recurrent neuro fuzzy control design for tracking of mobile robots via hybrid algorithm. *Elsevier Expert Systems with Applications*, 36(5), 8993–8999. doi:10.1016/j.eswa.2008.11.051
- Li, H., & Yang, S. X. (2003, Sep). A behavior-based mobile robot with a visual land-mark recognition system. *IEEE Transactions on Mechatronics*, 8(3), 390–400. doi:10.1109/TMECH.2003.816818
- Li, T. H. S., Chang, S. J., & Chen, Y. X. (2003). Implementation of human-like driving skills by autonomous fuzzy behavior control on an FPGA-based car-like mobile robot. *IEEE Transactions on Industrial Electronics*, 50(5), 867–880. doi:10.1109/TIE.2003.817490
- Li, T. H. S., Chang, S. J., & Tong, W. (2004a). Fuzzy target tracking control of autonomous mobile robots by using infrared sensors. *IEEE Transactions on Fuzzy Systems*, 12(4), 491–501. doi:10.1109/TFUZZ.2004.832526
- Li, T. H. S., Chang, S.-J., & Tong, W. (2004b). Fuzzy target tracking control of autonomous robots by using infrared sensors. *IEEE on Fuzzy Systems*, 12(4), 491–501. doi:10.1109/TFUZZ.2004.832526
- Li, W., Ma, C., & Wahl, F. M. (1997). A neuro-fuzzy system architecture for behavior-based control of a mobile robot in unknown environments. *Fuzzy Sets and Systems*, 87(2), 133–140. doi:10.1016/S0165-0114(95)00015-1
- Liang, Y., Xu, L., Wei, R., & Hu, H. (2010). Adaptive fuzzy control for trajectory tracking of mobile robot. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* (pp. 4755–4760). Taiwan.
- Liu, J., Yang, J., Liu, H., Tian, X., & Gao, M. (2017). An improved ant colony algorithm for robot path planning. *Soft Computing*, 21(19), 5829–5839. doi:10.1007/s00500-016-2161-7
- Liu, Q., Lu, Y. G., & Xie, C. X. (2006). Fuzzy obstacle-avoiding controller of autonomous mobile robot optimized by genetic algorithm under multi-obstacles environment. *IEEE 6th World Congress on Intelligent Control and Automation* (pp. 3255–3259). China.
- Liu, X., & Gong, D. (2011). A comparative study of A-star algorithms for search and rescue in perfect maze,” 2011 International Conference on Electric Information and Control Engineering (pp.24–27), Wuhan. doi: 10.1109/ICEICE.2011.5777723
- Lu, L., & Gong, D. (2008). Robot path planning in unknown environments using particle swarm optimization. *IEEE International Conference on Natural Computation (ICNC)* (pp. 422–426). China.
- Luo, R. C., & Chang, C. C. (2012). Multisensor fusion and integration: A review on approaches and its applications in mechatronics. *IEEE Transactions on Industrial Informatics*, 8 (1), 49–60. doi:10.1109/TII.2011.2173942
- Ma, X., Li, X., & Qiao, H. (2001). Fuzzy neural network-based real-time self-reaction of mobile robot in unknown environments. *ELSEVIER Mechatronic*, 11(8), 1039–1052. doi:10.1016/S0957-4158(00)00061-1
- Maram Alajlan, K., Koubaa, A., Chaari, I., Hachemi Bennaceur, K., & Ammark, A. (2001). Global path planning for mobile robots in large-scale grid environments using genetic algorithms.
- Marichal, G. N., Acosta, L., Moreno, L., Mendez, J. A., Rodrigo, J. J., & Sigut, M. (2001). Obstacle avoidance for a mobile robot: A neuro-fuzzy approach. *Fuzzy Sets and Systems*, 124(2), 171–179. doi:10.1016/S0165-0114(00)00095-6
- Martinez, R., Castillo, O., & Aguilar, L.T. (2009). Optimization of interval type-2 fuzzy logic controllers for a perturbed autonomous wheeled mobile robot using genetic algorithms. *ELSEVIER Information Sciences*, 179(13), 2158–2174. doi:10.1016/j.ins.2008.12.028
- Masehian, E., & Amin-Naseri, M. R. (2004). A Voronoi diagram–visibility graph–potential field compound algorithm for robot path planning. *Journal of Robotic System*, 21(6), 275–300. doi:10.1002/rob.20014
- Masehian, E., & Sedighzadeh, D. (2010). A multi-objective PSO-based algorithm for robot path planning. *IEEE International Conference on Industrial Technology (ICT)* (pp. 465–470). Chile.
- Meier, D., Tullumi, I., Stauffer, Y., Dornberger, R., & Hanne, T. (2017, August). A novel backup path planning approach with ACO. In 2017 5th International Symposium on Computational and Business Intelligence (ISCBI) (pp. 50–56). IEEE. doi:10.1016/j.ijcard.2017.04.017
- Ming, L., Zailin, G., & Shuzi, Y. (1996). Mobile robot fuzzy control optimization using genetic algorithm. *ELSEVIER Artificial Intelligence in Engineering*, 10(4), 293–298. doi:10.1016/0954-1810(96)00006-4
- Mohanta, J. C., Parhi, D. R., & Patel, S. K. (2011). Path planning strategy for autonomous mobile robot navigation using Petri-GA optimisation. *Computers and Electrical Engineering*, 37(6), 1058–1070. doi:10.1016/j.compeleceng.2011.07.007
- Montaner, M. B., & Ramirez-Serrano, A. (1998). Fuzzy knowledge-based controller design for autonomous robot navigation. *Elsevier Expert Systems with Applications*, 14(1), 179–186. doi:10.1016/S0957-4174(97)00059-6
- Motlagh, O., Nakhaeina, D., Tang, S. H., Karasfi, B., & Khaksar, W. (2014). Automatic navigation of mobile robots in unknown environments. *Neural Computing and Applications*, 24(7), 1569–1581. doi:10.1007/s00521-013-1393-z
- Mustafa, S., Ozdemirel Nur, E., & Sinan, K. (2000). Theory and methodology: A selforganizing neural network approach for the single AGV routing problem. *European Journal of Operational Research*, 121, 124–137.
- Muthu, T., Thierry Gloude, R., Swaminathan, S., & Satish Kumar, L. (2012). Fuzzy logic controller for autonomous navigation. *IEEE International Conference on Communications and Signal Processing (ICCS)* (pp. 81–92). India.
- Nichols, E., McDaid, L. J., & Siddique, N. (2013). Biologically inspired SNN for robot control. *IEEE Transactions on Cybernetics*, 15(2), 115–128. doi:10.1109/TSMCB.2012.2200674
- Omrane, H., Masmoudi, M. S., & Masmoudi, M. (2016). Fuzzy logic based control for autonomous mobile robot navigation. *Computational Intelligence and Neuroscience*, 2016, 1–10. doi:10.1155/2016/9548482
- Park, K. H., Kim, Y. J., & Kim, J. H. (2001). Modular Q-learning based multi-agent cooperation for robot soccer. *ELSEVIER Robotics and Autonomous Systems*, 35(2), 109–122. doi:10.1016/S0921-8890(01)00114-2
- Patino, H. D., & Carelli, R. (2004). Neural network-based optimal control for autonomous mobile vehicle navigation. In *IEEE International Symposium on Intelligent Control* (pp. 391–396). Taipei, Taiwan.
- Payne, D. B., & Stern, J. R. (1985). Wavelength-switched passively coupled single-mode optical network,” in *Proc. IOOC-ECOC* (pp. 585–590). Boston, MA, USA.

- Pradhan, S. K., Parhi, D. R., & Panda, A. K. (2006). Neuro-fuzzy technique for navigation of multiple mobile robots. *Springer Fuzzy Optimization and Decision Making*, 5(3), 255–288. doi:10.1007/s10700-006-0014-z
- Pratihari, D. K., Deb, K., & Ghosh, A. (1999). A genetic-fuzzy approach for mobile robot navigation among moving obstacles. *International Journal of Approximate Reasoning*, 20 (2), 145–172. doi:10.1016/S0888-613X(98)10026-9
- Purian, F. K., & Sadeghian, E. (2013) Mobile robots path planning using ant colony optimization and fuzzy logic algorithms in unknown dynamic environments. *IEEE International Conference on Control, Automation, Robotics and Embedded Systems(CARE)* (pp. 1–6). India.
- Qu, H., Xing, K., & Alexander, T. (2013). An improved genetic algorithm with co-evolutionary strategy for global path planning of multiple mobile robots. *Elsevier Neurocomputing*, 120, 509–517. doi:10.1016/j.neucom.2013.04.020
- Rai, N., & Rai, B. (2013). Neural network based closed loop speed control of DC motor using arduino Uno. *International Journal of Engineering Trends and Technology*, 4(2), 137–140.
- Rossomando, F. G., & Soria, C. M. (2015). Design and implementation of adaptive neural PID for non linear dynamics in mobile robots. *IEEE Latin America Transactions*, 13(4), 913–918. doi:10.1109/TLA.2015.7106337
- Rusu, C. G., Birou, I. T., & Szoke, E. (2010) Fuzzy based obstacle avoidance system for autonomous mobile robot. *IEEE International Conference on Automation Quality and Testing Robotics (AQTR)* (pp. 1–6). Romania.
- Rusu, P., Petriu, E. M., Whalen, T. E., Cornell, A., & Spoelder, H. J. (2003). Behavior-based neuro-fuzzy controller for mobile robot navigation. *IEEE Transactions on Instrumentation and Measurement*, 52(4), 1335–1340. doi:10.1109/TIM.2003.816846
- Saleh Alija, A. (2015). *Analysis of Dijkstra's and A* algorithm to find the shortest path* (Doctoral dissertation), Universiti Tun Hussein Onn Malaysia.
- Samsudin, K., Ahmad, F. A., & Mashohor, S. (2011). A highly interpretable fuzzy rule base using ordinal structure for obstacle avoidance of mobile robot. *Applied Soft Computing*, 11(2), 1631–1637. doi:10.1016/j.asoc.2010.05.002
- Sariff, N. B., & Buniyamin, N. (2009) Comparative Study of Genetic Algorithm and Ant Colony Optimization Algorithm Performances for Robot Path Planning in Global Static Environments of Different Complexities. *IEEE International Symposium on Computational Intelligence in Robotics and Automation (CIRA)* (pp. 132–137). South Korea. doi:10.1177/1753193408095877
- Schler, F. (2012). 3d path planning for autonomous aerial vehicles in constrained spaces (Ph.D. thesis), Department of Electronic Systems, Faculty of Engineering and Science, Aalborg University, Aalborg, Denmark. doi:10.1094/PDIS-11-11-0999-PDN
- Sedighi, K. H., Ashenayi, K., Manikas, T. W., Wainwright, R. L., & Tai, H.-M. *Autonomous local path-planning for a mobile robot using a genetic algorithm*.
- Selekwa, M. F., Dunlap, D. D., Shi, D., & Collins, E. G. (2008). Robot navigation in very cluttered environments by preference-based fuzzy behaviors. *Robotics and Autonomous Systems*, 56(3), 231–246. doi:10.1016/j.robot.2007.07.006
- Soltani, A. R., Tawfik, H., Goulermas, J. Y., & Fernando, T. (2002). Path planning in construction sites: Performance evaluation of the dijkstra, A*, and GA search algorithms. *ELSEVIER Advanced Engineering Informatics*, 16(4), 291–303. doi:10.1016/S1474-0346(03)00018-1
- Soylu, M., Özdemirel, N. E., & Kayaligil, S. (2000). A self-organizing neural network approach for the single AGV routing problem. *European Journal of Operational Research*, 121(1), 124–137.
- Surmann, H., Huser, J., & Peters, L. (1995). A fuzzy system for indoor mobile robot navigation, *Fourth IEEE International Conference on Fuzzy Systems, FUZZ-IEEE 95* (pp 83–88). doi:10.1177/014860719501900183
- Wang, X., & Yang, S. X. A. (2003) Neuro-fuzzy approach to obstacle avoidance of a nonholonomic mobile robot. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronic* (pp. 29–34). Japan.
- Wong, C., Wang, H., & Li, S. (2008). PSO-based motion fuzzy controller design for mobile robots. *International Journal of Fuzzy Systems*, 10(1), 284–292.
- Xiao, H., Liao, L., & Zhou, F. (2007) Mobile robot path planning based on Q-ANN. *IEEE International Conference on Automation and Logistics, China*, pp. 2650–2654.
- Xiong, B., & Shiru, Q. U. (2010). Intelligent vehicle's path tracking based on fuzzy control. *Journal of Transportation Systems Engineering and Information Technology*, 10(2), 70–75. doi:10.1016/S1570-6672(09)60034-9
- Yan, F., Liu, Y.-S., & Xiao, J.-Z. (2013). Path planning in complex 3D environments using a probabilistic roadmap method. *International Journal of Automation and Computing*, 10(6), pp. 525–533. doi:10.1007/s11633-013-0750-9
- Yang, S. X., Hu, T., Yuan, X., Liu, P. X., & Meng, M. A. (2003). Neural network based torque controller for collision-free navigation of mobile robots. *IEEE International Conference on Robotics and Automation (ICRA)* (pp. 13–18). Taiwan.
- Yang, S. X., & Meng, M. (2001). Neural network approaches to dynamic collision-free trajectory generation. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 31(3), 302–318. doi:10.1109/3477.931512
- Yang Simon, X., & Max, M. (2000). An efficient neural network approach to dynamic robot motion planning. *Neural Networks*, 13, 143–148. doi:10.1016/S0893-6080(99)00103-3
- Yilmaz, N. K., Evangelinos, C., Lermusiaux, P. F. J., & Patrikalakis, N. M. (2008). "Path planning of autonomous underwater vehicles for adaptive sampling using mixed integer linear programming. *IEEE Journal of Oceanic Engineering*, 33(4), pp. 522–537. doi:10.1109/JOE.2008.2002105
- Yousfi, N., Reik, C., Jallouli, M., & Derbel, N. (2010) Optimized fuzzy controller for mobile robot navigation in a cluttered environment. *IEEE 7th International Multi-Conference on Systems, Signals and Devices* (pp. 1–7). Amman, Jordan.
- Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning-I. *ELSEVIER Information Science*, 8(3), 199–249. doi:10.1016/0020-0255(75)90036-5
- Zhang, N., Beetner, D., Wunsch, D. C., Hemmelman, B., & Hasan, A. (2005) An embedded real-time neuro-fuzzy controller for mobile robot navigation. *IEEE International Conference on Fuzzy Systems* (pp. 319–324). USA.
- Zhang, Q., & Li, S. (2007) A global path planning approach based on particle swarm optimization for a mobile robot. *International Conference on Robotics, Control*

- & Manufacturing Technology World Scientific and Engineering Academy and Society (WSEAS) (pp. 263–267). China.
- Zhao, T., & Wang, Y. A. (2012) Neural-network based autonomous navigation system using mobile robots. IEEE 12th International Conference on Control, Automation, Robotics & Vision (ICARCV) (pp. 1101–1106). China.
- Zhu, A., & Yang, S. X. (2007). Neurofuzzy-based approach to mobile robot navigation in unknown environments. IEEE transactions on systems. *Man*, 37(4), 610–621.
- Zou, A. M., Hou, Z. G., & Fu, S. Y., (2006) Tan M neural networks for mobile robot navigation: A survey. *Advances in Neural Networks-ISNN*(pp. 1218–1226). China. doi:[10.1037/0735-7044.120.6.1218](https://doi.org/10.1037/0735-7044.120.6.1218)



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