A Review on Role of Artificial Potential Field Approach in Navigation of Robot

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***Abstract*— This review article discusses the research of robot navigation. This approach is based on the Artificial Potential field. Despite being the most well-known navigation strategy, Artificial Potential Field (APF) still has flaws such as easy fall into local minima, poor success rate, and inefficient path planning. The navigation of robots is still one of the most complex and hard functions to do. This paper examines the usage of the Artificial Potential field technique for numerous applications in various sectors, as well as the navigation across static and dynamic situations. The report finishes with tabular data and graphs comparing the simulation results for each robot application.**

Keywords—Navigation, Obstacle avoidance, Artificial Potential Field

I. INTRODUCTION

Obstacle avoidance by the manipulator Path planning is the process of determining a viable path from the starting point to the end point of the manipulator. Throughout the process, the manipulator must avoid colliding with any obstacle. This is an advanced three-dimensional obstacle path planning issue in environment. The path planning problem, [1] static as well as dynamic depends upon the information available in the space. Path planning in a partially or completely unknown environment seems to be more realistic, but also more difficult.

In the navigation of robot to solve the problems of path planning there are various approaches such as [2] Vonoroi Diagram (VD), Visibility Graph (VG), Virtual Force Field, Virtual Force Histogram, Neural Network based approach, Fuzzy logic, Cell Decomposition, Roadmap approach, Artificial Potential Field Approach etc.

Vonoroi diagrams are often use for path planning and obstacle avoidance in robot operating system. Creating robot's environment in Vonoroi diagram, it creates partitions of space then into regions based on robot's vicinity to the obstacle. This enables to detect free space available in environment and navigate efficiently according to it. Visibility graphs are one type of graph that represents the connectivity between different points which is available in environment. This also can include the nodes representing points that are in interest or can also be edges that are representing straight- line paths. By selectively incorporating points unobstructed by obstacle, visibility graphs streamline the process of optimization, and enhances the efficiency of navigation, within the intricate surrounding. Virtual force fields are in the domain of robotics are sophisticated mathematicsl constructs intricately designed to replicate complex dynamics between surrounding and the robot. It plays many roles in the field of robotics such as path planning, obstacle avoidance, and navigation.

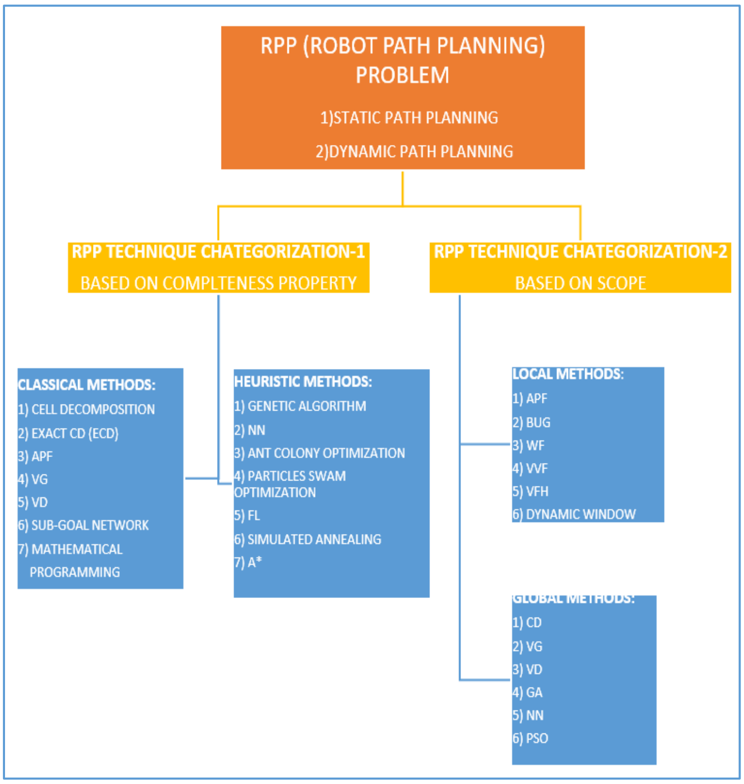

Fig. 1. Classification of mobile robots navigation techniques [4]

Robot path planning is mainly devided in to two catagories as shown in Fig [1], Firstly, based on the completeness of the property, and secondly based on the scope. The completeness of property is been catagoried into two sub parts, classical and Hueristic. The main aim of the classical algorithms is to find out the optimal path to travel if there any otherwise proving that there is no soltion for it. While in hueristic algorithms, they tries to find the better path in no time but they does not take full responsibilty to find the soltion. Also, RPP based on the scope also derived in 2 subcatagories, Local method and Global method. Local method, uses the sensor information as they does not know the enviornmet or any othe partial information and about Global approach they vreates a hazard free path based on the previously known path.

Tharinder Veerakon [4] have proposed a tabular data of basic fundamental comparison of some of the approaches as shown below in table 1.

Table 1: Classification of algorithms for planning paths of mobile robots

ALGORITHM	ADVANTAGES	DISADVANTAGES
APF	REAL TIME, 2D OR 3D, POINT, /RIGID ROBOT	NON-COMPLETE, NON-OPTIMAL, LOCAL MINIMA
CD	COMPLETE, SOUND, 2D AND 3D, POINT, OR RIGID ROBOT	NON-OPTIMAL, HEAVY COMPUTATION, TIME
ECD	COMPLETE, 2D, POINT ROBOT	NON-OPTIMAL, HEAVY COMPUTATION, TIME
ACD	LOW COMPUTATION, 2D, POINT ROBOT	NON-OPTIMAL, NON-COMPLETE
VG	COMPLETE, OPTIMAL LENGTH PATH, 2D OR 3D, POINT ROBOT, STSTIC ENVIORNMENT	NON-OPTIMAL, HEAVY COMPUTATION,TIME COMPLEXITY, PATH CLOSER TO OBSTAES
VD	COMPLETE, SAFER PATH, 2D OR ARBITRARY, POINT ROBOT	NON-OPTIMAL, LONG RANGE SENSOR FOR LOCAL PATH PLANNING
BUG	COMPLETE, 2D, POINT ROBOT	NON-OPTIMAL, LONG PATH, TIME COMPLEXITY
HEURISTIC	LESS TIME, PARALLEL SEARCH, POINT ROBOT	NON-COMPLETE, NOT SOUND

As we know the current trend in robotics having shifting from industrial to more challenging parts, such as in Healthcare industry to perform surgeries, underwater robots to explore the sea in deep etc. In such cases it makes so much hard to make the right path and cannot be able to identify fully the obstackle present in it's route. To tackle this problem khatib [3] proposed an approach in 1985 namely Artificial Potential Field. This method is commonly used for mobile robot path planning. It is also know for it's elegant mathematical analysis and simplicity. Artificial Potential Field

3.1 Introduction

The traditional Artificial Potential Field (APF) approach entails creating an appealing artificial potential field around the target site attracts the robot and repels it using an artificial potential field the robot is being repelled by barriers. For the last several decades, optimization algorithm development has occupied a large portion of scholars' attention. Optimization methods and algorithms can be classed as stochastic or deterministic based on their nature. [19] Having been influenced by the robot advances to its destination based on these two combined potentials. While avoiding the impediments in its path, it arrives at its target. The manner in which the way this algorithm works is that, despite the fact that the potentials are only a few, They can create an artificial force field that, in turn, can generate an artificial force field. In turn, when paired with the condition of the robot and artificial dynamics can generate a synthetic velocity and acceleration for use in simulations a reference that may be used to regulate the robot's posture in real time.

The Artificial Potential Field (APF) approach, gives a virtual potential to the target location that draws the robot as it moves away to the stumbling blocks, a virtual potential that repels the as it draws closer to them, the robot becomes more obnoxious. The robot is moving around the world while avoiding the obstacles along the way to the destination it's on its way.

Potential field techniques, which are widely used for real-time collision-free path planning. Before using this strategy, the robot becomes trapped at local minima achieving the desired setup and colleagues have designed a real-time mobile obstacle avoidance strategy robot. The navigation algorithm considers a variety of factors a mobile robot's dynamic behavior and solves the local minimum a difficulty with traps the repulsive force is substantially stronger than the attractive force. They are considering the appealing force. To put it another way, the goal location is not the absolute lowest point in the overall potential field. As a result, the robot is unable to achieve its objective to the neighboring stumbling block [6]. Robots detect their surroundings via sensors; nonetheless, the difficulty of perception delay occurs, particularly for high-speed robots in congested, unfamiliar situations. Perception latency is the amount of time it takes for a robot to detect its surroundings and digest the data it collects before issuing control orders. The higher the relative speed between the robot and the object, the quicker the detect speed needed to create a safe movement to prevent a collision.

SR. NO.	SENSOR	PRINCIPLE	ADVANTAGES	DISADVATAGES
1	Ultrasonic sensor	The robot's distance from the barrier is estimated using the difference in time between transmitting and receiving ultrasonic signals, as well as the soundwave.	Low cost.High frequency.Short wavelength.Hard ware implementation is sample.	Short measure distance (5–10 m).There is interference between multiple ultrasonic sensors.There is minimum detection blind spot (tens of millimeters). Influenced by air temperature and humidity.
2	Infrared sensor	The distance is estimated using triangle geometry and the reflected beam deviation of the barrier.	Simple, cheap, fast. Small size.Not influenced by visible light.Not interfered by the electromagnetic wave.Strong environmental adaptability.	Measurement error is greatly influenced by the environmental factors such as color and direction of the detected object, luminous beam.Poor measurement accuracy.Cannot detect transparent and black objects
3	Laser sensor	The distance is computed using the time difference between the primary signal and the reflected signal.	Long measure distance.Fast speed.High precision.Wide detection range.Light resistance.	Expensive.It is not suitable for the distance with high measurement accuracy requirement.
4	Monocular vision	The collected image is compared to reference images stored in memory.	Single structure.Flexible motion.Easy to calibration.	Need to build and maintain a huge target feature database.Cannot detect the transparent object.
5	Binocular vision	Distance is estimated by computing the difference between two pictures acquired by two cameras, without considering the type of obstruction.	Target feature database is not needed.High precision compared to monocular vision.	Large computational complexity.High hardware cost.

Fig. 2. Comparison of today's most extensively used sensors.

3.2 Application of APF in Robots

A. Wheeled Mobile Robot Navigation

Wheeled Mobile Robots (WMR) are the most important choice for to be utilized in the place where peoples need to work in hazardous situations like explosive industries, exploration industries, radioactive chemical factories. WMR eliminates this situation as it can work in any conditions and are autonomous.

The formation control problem of a collection of non-holonomic mobile robots—in which each WMR travels in a predetermined direction while preserving a geometric formation in a two-dimensional space—is examined in this paper. In order to avoid the robots colliding with the obstacles before they reach the destination location, the APF approach is used. [11]. To work in this type of environment a mobile robot has to decide the exact direction or carry out a process exactly as it has to be done due to not fixation of robot. To carry out this process and to reach the required target from its original position and this approach is called as Maneuvering

Planning. According to, Park et al. employing the simulated annealing algorithm in conjunction with the basic APF approach to address the problem that the original APF-based method is easily trapped in the local minimum. [21] Priyanka Sudhakaraa proposed [11] a route planning strategy based on the features of water current stream flow utilizing a grid-potential approach. The flow of the stream, like the water current stream, goes from the high potential field to the low potential field, and the headstream assumes the robot's original location. When the water current stream runs, the trajectory of the stream generates a reasonable obstacle-avoiding path from the starting point to the desired location.

Problems to be solved	WMR'S MULTIPLE OR SINGLE	Methods	Improvements	Advantages	literatures
Navigation	Single	Simulated annealing	Is a feasible path	Improve performance of the original APF that is easy to trap into the local minimum	Park et al.[7]
Navigation	Single	Improve potential function	Is a feasible path	Improve the vibrating problem	Shi et al.[12]
Navigation	Single	Introduce gravity chain concept into the APF	Is a feasible path	Improve the target nonreachable problem	Tang et al.[13]
Navigation	Single	Regression search &0x002B; the APF	Environmental information is known completely	Is the shortest path from source to target	Li et al.[14]
Formation	Multiple	Introduce rotating fields into the APF	Not clearly mention collision avoidance objects	Improve local minimum performance	Azhar and Bilal Kadri[16]
Formation	Multiple	Improve potential function	Not interrobots consider collision avoidance	Consider connectivity maintenance during collision avoidance	Yang et al.[17]
Navigation	Single	Introduce collision time concept into the APF	Only consider single WMR	Avoid dynamic obstacles	Li et al.[18]

Fig. 3. Comparison of today's most extensively used sensors.[11]

A scenario-based map has been created depending on the environment. The physical workspace of the robot is represented by a two-dimensional array cell. Each cell on the map contains the potential function value as well as the grid coordinate values. Local sensors mounted on the robot collect information about the local environment. This will also update the information in the cells. In this case, the heuristic searching function makes use of the potential function to trace the route during processing [4].

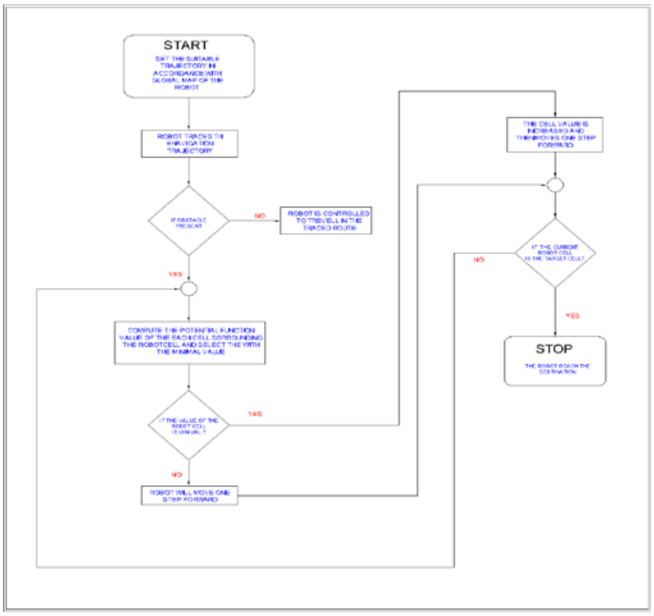

Fig. 4. Flowchart for trajectory generation for WMR

This study proposes a grid-potential strategy for route design that takes into account the features of water current stream flow. The stream, like a water current, travels from high to low potential fields, with the headstream assuming the robot's beginning location. When a water current stream goes from its starting point to its destination, it creates a route that avoids obstacles. The map's cells show the potential function value and grid coordinates. Local sensors put on the robot collect local situation information. This will also update the cells' information. The heuristic searching function uses the potential function to trace the path during processing.

B. Industrial Robot

Station changeover is a crucial part of multi-station industrial robot welding systems. A fixed instruction track is used in traditional station conversion, however in today's complex industrial output environment, a constant track usually can't keep up with demand.

Based on the obstacle data conveyed by the system's external sensor, the deadlock path can be fully planned and conveyed back to the control cabinet via the local area network, enabling the industrial robot's implementation trajectory to be controlled and the station transfer to be realised. The general adaptability of the multi-station welding system is improved, and the situation where the station changeover trajectory needs to be changed in response to changing work environment is avoided, resulting in significant boost in work efficiency.

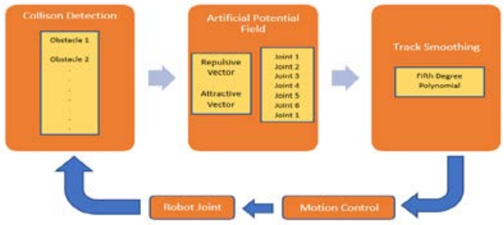

Fig. 5. Overall system config. For ostackle avoidance and path planning in Industrial Robot

The number of barriers is shown to be 6 in this scenario. The welding station change, in general, poses less obstacles than the preceding scenario. In the tough case, the detection technique can also resolve the collision-free path smoothly, demonstrating that the methodology may be applied. With fewer barriers in real-world scenarios [5].

The approach involved incorporating obstacle avoidance information into the potential field via the gravity chain to create a steering angle tangent to the rubber band. To address the local minima problem, link the beginning and end of the obstacle potential field, rather than the angle of the fake potential field. The proposed-APF (P-APF) method was used to find the objective point in unknown 2D surroundings, avoiding deadlock and non-reachability issues associated with mobile robot navigation. However, this technique only calculates effective front-face barrier information based on velocity direction, including size and shape. [23]

Robots are believed to travel in a direction aligned with natural potential fields. The angle direction at every point in the field is determined by the combination of a repellent force from the obstacle and an attracting force towards the objective (Fig 6).

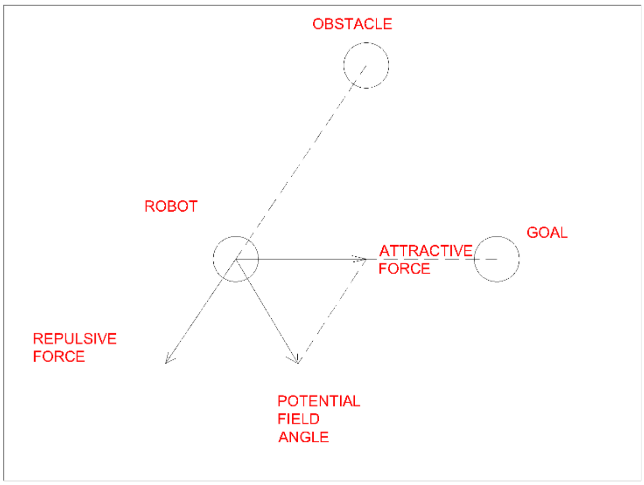

Fig. 6. Resultant angle directions in eapf

A dual-arm robot's complicated construction prevents the manipulator from being utilized as a mass point for calculating force and movement in an artificial potential field. The classic artificial potential field algorithm cannot be employed with dynamic obstacles as goal points. A speed field with improved artificial potential field algorithm is proposed. This method establishes an artificial potential field in Cartesian space at the manipulator's joints and converts the potential field force received by each joint into a differential velocity for calculation (see Figure 8).[23]

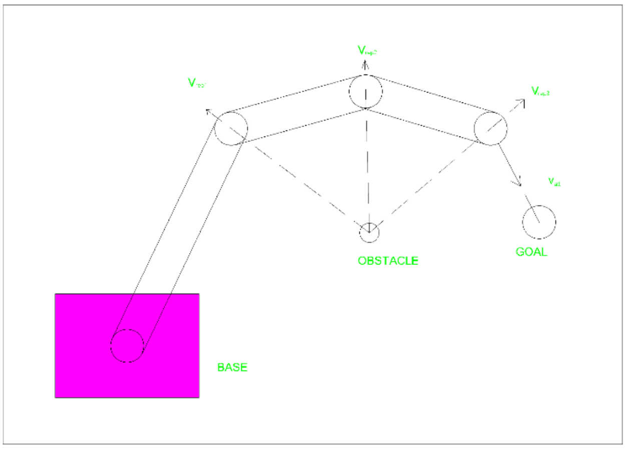

Fig. 7. The speed of a robot in the field of artificial potential.

Four path planning assignments include a fixed barrier and objective condition. The impediment in each assignment varies in location. All four situations resulted in collision-free optimum pathways. Four path-planning tasks include a moving barrier and objective condition. In the first three situations of, the objective point and impediment travel in opposite directions. The suggested EAPF's resilience is demonstrated by randomly moving the target point and obstacle.

Four path-planning tasks in a multi-obstacle scenario with a fixed destination point. In the first sHOWS, the robot successfully avoided the two stationary obstacles and reached the stationary goal. For the next two illustrates how a robot may navigate a dynamic environment while avoiding obstacles. In the last, the robot successfully navigated a randomly shifting destination while avoiding three obstacles. The suggested evolutionary artificial potential field approach can design an ideal smooth path regardless of fixed or moving barriers and objective points.

C. Unmanned Aerial Robot

Unmanned aerial systems (UASs) are becoming more popular in the field of its diverse surveying and military applications. Automatic UASs require a collision-avoidance optimization method, also known as sense and avoid, to monitor the flight and alert the aircraft to critical avoidance moves. The artificial potential fields (APFs) method is a well-known collision-avoidance approach based on electric fields. Impediments (other planes) are portrayed as repellent charges, whereas objectives (waypoints) are depicted as attractive charges. These expenses are then added together to determine which route is the safest to move towards. Whereas the basic procedure is clear and simple, it can malfunction in a variety of conditions, including becoming caught in a local minimum. The utilisation of dynamic force fields that are based on the vehicle's position and velocity. The distance the aeroplane can fly in a second was used to build an elliptical force field in this analysis. The force field uses scalar changes to create a bigger and stronger field in front of the aircraft. As a consequence, the difference in bearing between the aircraft exerting the force and the aircraft feeling the force may be utilised to calculate the force exerted on another aircraft. A supplementary calculation is also carried out, which translates the applied force into a felt force. [8].

Jun Tang provides an efficient APF approach for multi-UAV trajectory planning and collision avoidance. UAVs from different groups optimize their paths in a 3D space model using various methodologies. The approach addresses jitter issues through dynamic step modification and climb strategy. [24]

The approach is confirmed by MATLAB simulations. This improved APF approach aims to offer a safe, viable, and stable path for a UAV to accomplish its mission. It also supports future research on path planning and obstacle avoidance. [24]

D. Humanoid Robot

Humans have designed their settings in proportion to their ergonomics, thus robots with the same physical physique as humans are more helpful than others. Humanoid robots that are completely adaptable to industrial contexts are yet not possible to create. Some research needs include stability, mapping, interfacing, computation, and grasping, and path planning makes humanoid robot navigation an unresolved challenge. The ultimate objective for a humanoid robot is for it to be able to work in any situation. Because the actual world is changeable, it is hard to save all surroundings in robot memory. This means that humanoid robots will have to work in unfamiliar situations. For mobile robots, the placement of barriers, restricted zones, and free areas must be established throughout the path design process. This information might be obtained via an imaging system in humanoid robots [9].

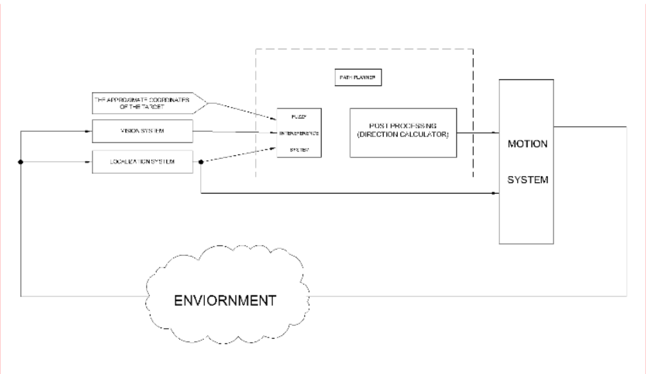

Fig. 8. Path Planning for humanoid robot

E. Underwater Robot

Because there is no direct relationship between the remotely operated underwater vehicle (AUV) and its mothership, because the AUV's power and energy are constrained, and the ocean environment is complicated and unpredictable, underwater path planning and navigation technology development is essential for avoiding obstacles and effectively completing underwater activities. Many scholars have concentrated their efforts on combining established ground mobile robot path technology and implement into underwater vehicle route planning, notably the artificial potential field path planning technique, which is widely used in the field of ground mobile robots.

The unique path planning method combines the artificial potential field technique and the velocity synthesis algorithm. After the combination of ocean current velocity and AUV velocity, the artificial potential field exactly defines the velocity direction.

The non - periodic flow of saltwater that is typically constant but changes with the seasons, climate, topography, and depth of the sea. Ocean current is a complex time-space variable that is challenging to mathematically express. In a constrained marine region and for a certain time period, the flow rate and direction, on the other hand, remain relatively constant. The AUV's energy is also limited, and it can only move inside a specific sea zone. As a result, the ocean current is a static vector in the simulation. To put it another way, the value and direction remain the same [9].

II. CONCLUSION

The Study of Application of APF in various categories of robot have been studied. From this study it is clearly state that robot no matter which category it is from path planning is the utmost problem in the navigation system to carry out the given task. It is also observed that for different conditions or different environment require some modification of APF approach. APF has used successfully for path planning of drone, underwater robot, industrial robot, humanoid robot. It is a very fast and accurate technique due to its real time path planning ability. Due to its ability of making suitable route in real time it gives response in proper time and a widely adopted technique in the industry. While this method is computationally effcient and intuitive, making them more suitable for real time applications. This method can handle dynamic environments and can easily extended to multi robot system.

REF NO.	APPLICATIONS	PATH PALNNING IN ORESENCE OF		ROBOTS USED	PATH PLANNING	YEAR
		STATIC OBSTACLE	DYNAMIC OBSTACLE			
1	INDUSTRIAL ROBOTS	Y	N	Y	Y	2019
3	UNMANNED AERIAL VEHICLE	Y	Y	Y	Y	2014
4	HUMANOID ROBOT	Y	N	Y	Y	2015
6	WHEELED MOBILE ROBOT	Y	Y	Y	Y	---
7	INDUSTRIAL ROBOTS	Y	N	Y	Y	2020
8	WHEELED MOBILE ROBOT	Y	Y	Y	Y	2015
9	WHEELED MOBILE ROBOT	Y	Y	Y	Y	1985
10	WHEELED MOBILE ROBOT	Y	Y	Y	Y	2018
12	WHEELED MOBILE ROBOT	Y	Y	Y	Y	2001
13	WHEELED MOBILE ROBOT	Y	N	Y	Y	2007
14	WHEELED MOBILE ROBOT	Y	Y	Y	Y	2010

Fig. 9. Number of papers for different applications.

[7] X`Ming Zhao And Xiaoqing Lv, Improved Manipulator Obstacle Avoidance Path Planning Based On Potential Field Method, Hindawi, Journal Of Robotics, 2020.

[8] Tharindu Weerakoon, Kazuo Ishii And Amir Ali Forough Nassiraei, An Artificial Potential Field Based Mobile Robot Navigation Method To Prevent From Deadlock, Jaiscr, 2015

[9] Khatib O; Real-Time Obstacle Avoidance For Manipulators And Mquiee Robots, Ieee, 1985

[10] Priyanka Sudhakaraa, Velappa Ganapathya, B.Priyadharshinia, Karthika Sundarana, Obstacle Avoidance And Navigation Planning Of A Wheeled Mobile Robot Using Amended Artificial Potential Field Method, International Conference On Robotics And Smart Manufacturing (Rosma2018), 2018.

[1] Shengnan Gai, Rui Sun,Shunjun Chen, Shuting Ji, 6-Dof Robotic Obstacle Avoidance Path Planning Based On Artificial Potential Field Method, International Conference On Ubiquitous Robots (Ur), 2019

[2] B.K. Patle A, Ganesh Babu L B, Anish Pandey C, D.R.K. Parhi D, A. Jagadeesh E, A Review: On Path Planning Strategies For Navigation Of Mobile Robot, Defence Technology 15, Elsevier, 2019.

[3] Jason Ruchti, Robert Senkbeil, James Carroll, Jared Dickinson, James Holt, And Saad Biaz, Unmanned Aerial System Collision Avoidance Using Artificial Potential Fields, Journal Ofaerospace Information Systems, 2014

[4] Mahdi Fakoor, Amirreza Kosari And Mohsen Jafarzadeh, "Revision On Fuzzy Artificial Potential Field For Humanoid Robot Path Planning In Unknown, Int. J. Advanced Mechatronic Systems, 2015.

[5] Chunlei Cheng, Daqi Zhu, Bing Sun, Zhenzhong Chu, Jianduo Nie And Sheng Zhang, Path Planning For Autonomous Underwater Vehicle Based On Artificial Potential Field And Velocity Synthesis, Ieee, 2015

[6] Young Wang, Xiaoxiao Li, Juan Zhang, Shuai Li, Zhiao Xu, Xuefeng Zhou, Review of wheeled Mobile robot collison avoidance under enviornment, 'Guangdong R & D Center for Technological Econo

[11] RM. 802, Guangzhou, Guangdong, PR China, Guangdong Key Laboratory of Modem Control Techndlogy Instiarte of Inteligent, Manufacturing, Guangdong Academy of Sciences, Guangzhou, Guangdong PR Chima, School of Engineering Swansea Uriversity, Swansea, UK, Foshan Tri-Co Intelligent Robot Technology Company Ltd. Foshan, Chima, SAGE, 2021

[12] Park MG, Jeon JH and Lee MC. Obstacle avoidance for mobile robots using artificial potential field approach with simulated annealing. In: 2001 IEEE International Symposium on Industrial Electronics (ISIE), Pusan, Korea, 12–16 June 2001, vol. 3, pp.1530–1535.

[13] Shi E, Cai T, He C, et al. Study of the new method for improving artificial potential field in mobile robot obstacle avoidance. In: IEEE International Conference on Automation and Logistics (ICAL), Jinan, China, 18–21 August 2007, pp.282–286.

[14] Tang L, Dian S, Gu G, et al. A novel potential field method for obstacle avoidance and path planning of mobile robot. In: IEEE international conference on computer science and information technology, Bradford, UK, 29 June–1 July 2010, vol. 9, pp.633–637.

[15] Li H, Wang Z and Ou Y. Obstacle avoidance of manipulators based on improved artificial potential field method. In: 2019 IEEE international conference on Robotics and Biomimetics (ROBIO), Dali, China, 6–8 December 2019, pp.564–569.

[16] Li G, Yamashita A, Asama H, et al. An efficient improved artificial potential field based regression search method for robot path planning. In: 2012 International Conference on Mechatronics and Automation (ICMA), Sichuan, China, 5–8 August 2012, pp.1227–1232.

[17] Azhar A and Bilal Kadri M. Empirical evaluation of formation control scheme based on artificial potential fields for a team of nonholonomic mobile robots. In: 2018 International Conference on Emerging Technologies (ICET), Islamabad, Pakistan, 21−22 November 2018, pp.1–5.

[18] Yang S, Bai W, Li T, et al. Neural-network-based formation control with collision, obstacle avoidance and connectivity maintenance for a class of second-order nonlinear multi-agent systems. Neurocomputing 2021; 439: 243–255.

[19] Li B, Chang J and Wu C. A potential function and artificial neural network for path planning in dynamic environments based on self-reconfigurable mobile robot system. In: 2012 IEEE international symposium on Safety, Security, and Rescue Robotics (SSRR)

[20] Priyanka Sudhakara, Velappa Ganapathy, *Member, Karthika Sundaran ,Graduate Student Member, IEEE* Research Scholar, School of Computing, SRM University,Kancheepuram-603203, Tamil Nadu, India. IEEE. 2018

[21] Priyanka Sudhakara, Velappa Ganapathya, B.Priyadharshinia, Karthika Sundarana, School of Computing, SRM Institute of Science and Technology, Kancheepuram,Tamil Nadu, India, Obstacle Avoidance and Navigation Planning of a Wheeled Mobile Robot using Amended Artificial Potential Field Method, Elsevier, 2018

[22] Hui Zhang, Yongfei Zhu, Xuefei Liu, Xiangrong Xu, School of Mechanical Engineering, Anhui University of Technology, Ma'anshan 243032, China, Analysis of Obstacle Avoidance Strategy for Dual-Arm Robot Based on Speed Field with Improved Artificial Potential Field Algorithm, MDPI, 2021

[23] Jun Tang , Jiayi Sun, Cong Lu, College of Systems Engineering, National University of Defense Technology, Changsha, China, Songyang LaoOptimized artificial potential field algorithm to multi-unmanned aerial vehicle coordinated trajectory planning and collision avoidance in three-dimensional environment, SAGE, 2019