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Navigation of Non-holonomic Mobile Robot Using Neuro-fuzzy Logic with Integrated Safe Boundary Algorithm

A. Mallikarjuna Rao[1] K. Ramji[2] B. S. K. Sundara Siva Rao[2] V. Vasu[3] C. Puneeth[1]

[1]Department of Mechanical Engineering, V R Siddhartha Engineering College, Vijayawada, A.P, India
[2]Department of Mechanical Engineering, A.U. College of Engineering, Andhra University, Visakhapatnam, A.P, India
[3]Department of Mechanical Engineering, National Institute of Technology-Warangal, Telangana, India

Abstract: In the present work, autonomous mobile robot (AMR) system is intended with basic behaviour, one is obstacle avoidance and the other is target seeking in various environments. The AMR is navigated using fuzzy logic, neural network and adaptive neuro-fuzzy inference system (ANFIS) controller with safe boundary algorithm. In this method of target seeking behaviour, the obstacle avoidance at every instant improves the performance of robot in navigation approach. The inputs to the controller are the signals from various sensors fixed at front face, left and right face of the AMR. The output signal from controller regulates the angular velocity of both front power wheels of the AMR. The shortest path is identified using fuzzy, neural network and ANFIS techniques with integrated safe boundary algorithm and the predicted results are validated with experimentation. The experimental result has proven that ANFIS with safe boundary algorithm yields better performance in navigation, in particular with curved/irregular obstacles.

Keywords: Robotics, autonomous mobile robot (AMR), navigation, fuzzy logic, neural networks, adaptive neuro-fuzzy inference system (ANFIS), safe boundary algorithm.

1 Introduction

Numerous path planning techniques have been proposed to navigate autonomous mobile robot (AMR) in a self-determinant path against obstacles to reach the goal/target. The artificial intelligence (AI) facilitates identification of path and to reach a specific target. Signals from sensors are considered as input to a microcontroller, which computes the logic to make a decision and generates a path for navigation by actuating direct current (DC) motors, coupled to both front wheels of the AMR.

Abdelmoula et al.[1] designed the AMR to follow the wall in an optimized path using fuzzy and neuro-fuzzy methods. Their algorithm integrates the information from various sensors and develops needed task for mobile robot to follow the wall.

Algabri et al.[2] applied adaptive neuro-fuzzy inference system (ANFIS) to navigate mobile robot for avoiding obstacles in path localization and planning. This combination algorithm can develop better path generation. Li and Choi[3] and Emhemed[4] used the ultrasonic sensors for mobile robot to sense distance and location of obstacles. They also utilized the fuzzy logic method to navigate the mobile robot. Brandão[5] proposed a non-linear supervised controller to navigate a robot through simulations and results are validated with experimentation. Ramdane et al.[6] and Faisal et al.[7] attempted to navigate the wheeled mobile robot (WMR) by fuzzy logic training through wireless message in dynamic environment. Meshram[8] simulated the leader robot to reach the destination while the follower robot maintains constant angle and relative distance between them.

Dubey et al.[9] proved that the path planning developed by reinforcement based learning is better than artificial neural network method. Hanumante et al.[10] recommended low cost mobile robot which navigated smoothly in unknown environments. He also proposed a better algorithm for smooth point to point path generation in collision free environment. Rashid et al.[11] projected the reciprocal orientation algorithm which yielded collision free and smooth navigation, where robot is self-communicating to find collision free path in experimental setup.

Fu et al.[12] suggested mini mobile robot navigation with 3D triangulation laser scanner which is cost effective. Here, movable parts are motivated by gear train, to attain 90° scanning vision angle.

Sezer and Gokasan[13] proposed an algorithm for novel obstacle avoidance which would be taken under the deliberation of non-holonomic constraint of the robot. The experimental results are very much satisfactory under static and dynamic obstacle environments. This proposed algorithm is well matched for mobile and industrial robots. Kim and

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Do[14] introduced a technology to overcome the moving obstacles while navigating the mobile robot. The image of the obstacle is taken by a single camera and subsequent analysis of image makes the decision of the recognition of the dynamic obstacles. Buniyamin et al.[15] has invented the bug algorithm for local path planning where the robot has identified the boundary of the obstacle through sensors and hence it can be move towards goal.

Sintob et al.[16] proposed the path planning of climbing robot with claws which can walk on the wall having smooth and rough surfaces. This work is noticeably useful for defence applications. This robot can climb elevated surfaces similar to the cat with the aid of 4 limbs. The design of this robot is so excellent that each leg contains 12 fishing hooks which can move independently on the rough wall surface.

Hashemi et al.[17] implemented that the path planning with Pi-fuzzy logic, connected through low level control system for a linear separate, self-motivated model of omnidirectional moving robot. The performance of this technique is compared against proportional-integral-derivative (PID) controller system and found satisfactory results.

Knudson and Tumer[18] assessed the reactive and learning algorithms for navigation of robot with scarce time and observations, in dissimilar situations like fire hazard and explosions. Tzafestas et al.[19] developed a chip for navigation of non-holonomic mobile robot which uses the digital fuzzy technique along with Xilinx micro-blanze soft processor core, which enabled a robot to navigate in smooth path by avoiding obstacles. Shi et al.[20] worked on local obstacle avoidance in unknown environment through various velocity space techniques such as method of curvature velocity, method of lane curvature and method of beam curvature in contemplation with dynamic environment conditions.

Mohanty et al.[21, 22] simulated autonomous mobile robot using different intelligent techniques like neural network (NN), fuzzy and ANFIS. In addition to that the usage of sensor for finding distance of an obstacle which improves the effectiveness of the navigation.

Kundu and Parhi[23] navigated underwater robot skilled with neural based adaptive fuzzy inference system. Petkovic et al.[24−26] applied ANFIS for adaptive robot gripper, also identified the stained joints in the robotic finger. Wang et al.[27] simulated the autonomous bay parking system intelligent with fuzzy system. Yan et al.[28] developed 3D path planning for an unmanned aerial vehicle in complex environments with probabilistic road map (PRM) method. Singh[29] developed an intelligent controller to navigate single or multiple robots in dynamic environments.

In the above literature survey mobile robot has been navigated to tag along a wall for obstacle avoidance. With the references mentioned [1, 8] simulation result was not supported with valid experimentation. Even though, there has been lot of research for path optimization of mobile robot, none of them focused on the experimentation on path planning of mobile robot by considering obstacles with irregular cross-sections like contour shape.

By considering the limitations of the previous work, an attempt has been initiated with experimental AMR is made intelligent with an integrated technique, ANFIS with safe noundary algorithm (SBA).

ANFIS with SBA technique is more logical for identifying lesser angle of rotation for overcoming of obstacles, with reference to the position and orientation of the AMR.

2 Method of navigation

2.1 Navigation of AMR

Navigation of AMR deals with the collision free path development, in various environments by obstacles having different cross sections/shapes, with aid of artificial intelligence (AI). Controller of AMR uses the data, obtained from the vehicle sensor system as in Fig. 1.

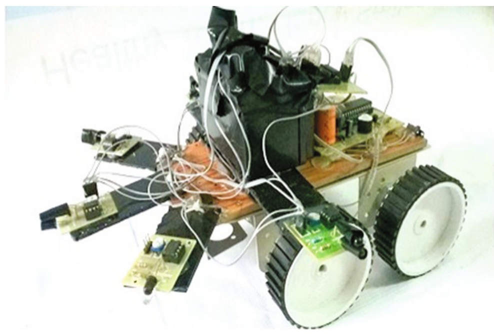


Fig. 1 Autonomous mobile robot

Initially, AMR scans a target/goal by rotating about its own vertical axis from 0° to 360°. Once the target is scanned, it will travels along the shortest path from the current position to target. The obstacles are detected with the aid of sensors and the necessary path planning action is generated, based on the strategy which is programmed in the microcontroller. This strategy requirement can be one among the three rules as follows and the logic is shown in Fig. 2.

1) Turn ($\theta_{moderate}$) to the left
2) Keep the same path
3) Turn ($\theta_{moderate}$) to the right.

Microcontroller of AMR is skilled through fuzzy logic techniques according to various environmental conditions. The controller receives signal from various sensors as input and the logical action is generated and fed to the wheels of AMR. The fuzzy logic controller drives the AMR with two basic deeds, obstacle avoidance and target seeking.

AMR is trained through back propagation neural network (BPNN) method for navigation, with same approach as fuzzy logic technique.

Finally, adaptive neuro-fuzzy inference system (ANFIS) is integrated with safe boundary algorithm, where inference mechanism is applied between fuzzy and neural network (NN) layers.

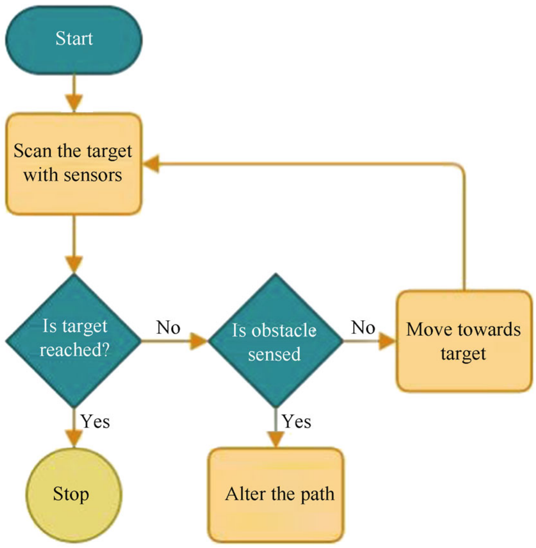


Fig. 2 Navigation strategy of AMR

2.2 Trajectory equation

Autonomous mobile robot is navigated in collision free environment by considering a path, S as a part of the route R, from the source $(x_s,\ y_s) \in R$ to destination $(x_d,\ y_d) \in R$.

Subsequently, navigation path is generated with sequence of line segments, $\mathrm{S}_i = 1,\ 2,\ 3,\ \cdots,\ n$; which are connected through intermediate points $(x_i,\ y_i)$.

Environment boundaries are defined as follows:

$$\begin{cases} En = (x, y) \in \mathbf{R}^2 \\ p \le x \le q \\ r \le y \le s \end{cases} \tag{1}$$

where p, q and r, s are the horizontal and vertical boundaries of the environment, En.

While mobile robot encounters an obstacle, it will be sensed by three sensors which are fastened in-front of AMR. Based on the distances and target angle identified by the sensors, artificial intelligence (AI) technique computes the decision for overcoming obstacles, with rotation about its own axis, either in clockwise or counter-clockwise directions.

2.3 Safe boundary concept

The proposed safe boundary concept improves non-contact crossover of AMR against obstacles as shown in Fig. 3. It was considered that the angle of rotation as

$$\Delta\theta_{moderate} = \theta_l(\text{or})\theta_r + 2^0. \tag{2}$$

AMR effectively crosses over obstacles without collision, by considering the safety margin.

Target angle, α is determined as follows:

$$\alpha = \tan^{-1}\left[\frac{(goal\ Y - robo\ y)}{(goal\ X - robo\ x)}\right].$$

Algorithm 1. Safe boundary concept

1) Initialize α, d and $d_{moderate}$
2) Move robot towards Target
3) **if** (d $\le d_{moderate}$) **then**
4) Stop robot
5) Evaluate d, d_1, d_2, θ_l and θ_r
6) $\theta_l = [\ \alpha - \sin^{-1}[(\frac{d}{d_1}) \times \sin(\alpha)]]$
7) $\theta_r = [\ \alpha - \sin^{-1}[(\frac{d}{d_2}) \times \sin(\alpha)]]$
8) **if** $(\theta_l \le \theta_r)$ **then**
9) $\Delta\ \theta_{moderate} = \theta_r + 2^{\circ}$
10) Turn AMR about its own axis, in CW direction-at an angle $\Delta\ \theta_{moderate}$
11) **else**
12) $\Delta\ \theta_{moderate} = \theta_l + 2^{\circ}$
13) Turn AMR about its own axis, in CCW direction-at an angle $\Delta\ \theta_{moderate}$
14) **end if**
15) Move robot with new orientation
16) **else**
15) Move robot with same orientation
18) **end if**
15) Stop robot, if the target is reached.

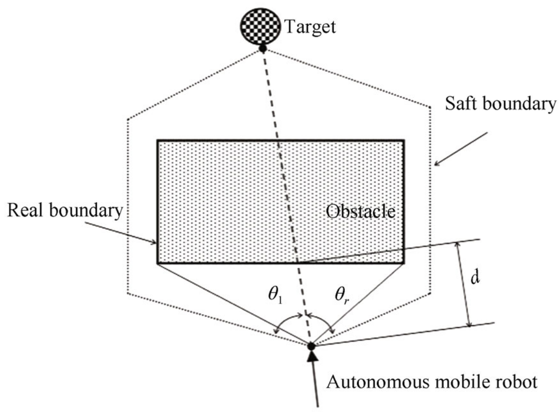


Fig. 3 Safe boundary concept

3 Kinematic analysis of autonomous mobile robot

Proposed AMR is designed with valid kinematic analysis, to generate experimental assessment for navigation in various environments. The wheels of the AMR were actuated by the signal generated from controller to attain desired position and orientation.

AMR is supported with four wheels with identical dimensions, where front two wheels are for driving and rear wheels are for support. Robot is in rectangular shape as viewed from top, having the center of gravity (CG) at point, G and geometrical center at point, P, as in Fig. 4.

Proposed AMR is taken into deliberation that no slip exists between wheel and floor.

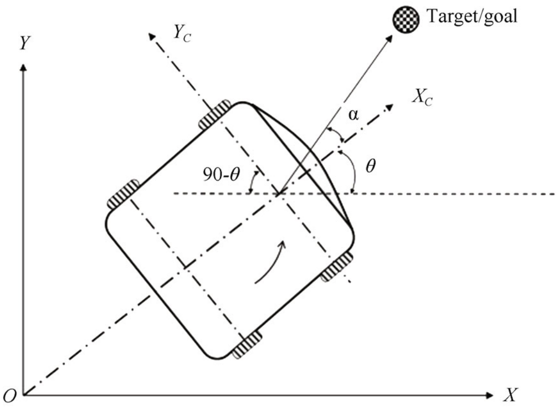


Fig. 4 Kinematic analysis of autonomous mobile robot

Robot position and direction is represented by means of the vector notation as in (3). Target velocity, $\vec{V}_T$

$$\vec{V}_T = 0.5\times[\vec{V}_R+\vec{V}_L]. \tag{3}$$

$$\vec{V}_R = r\times\vec{\omega}_R \text{ and } \vec{V}_L = r\times\vec{\omega}_L$$

where

$\vec{V}_R$ = Right wheel linear velocity

$\vec{V}_L$ = Left wheel linear velocity

$\vec{\omega}$ = Angular velocity of wheel

r = radius of wheel.

Position of AMR in the generalized coordinate system is a vector column matrix as

$$p = [X_c\ Y_c\ \theta]^{\rm T}. \tag{4}$$

By considering no slip condition between wheel and floor, the velocity component orthogonal to the plane of wheel is zero.

$$\left[\dot{Y}_c\cos(\theta)\quad -\dot{X}_c\sin(\theta)\quad -d\dot{\theta}\right]^{\rm T} = 0. \tag{5}$$

Let all kinematics constraints are independent of time, and are articulate as

$$\left[A(p)\times\dot{p}\right] = 0 \tag{6}$$

where $A(p)$ is constraint matrix

$$A(p) = \left[-\sin(\theta)\quad \cos(\theta)\quad -d\ \right] \tag{7}$$

$[A(p)\times\ \dot{p}]$ matrix is used to map motion in the global reference frame $[X\ Y]$ to the motion in terms of the local reference frame $[X_c\ Y_c]$.

The full rank matrix $C(p)$ is formed as[29]

$$C(p) = \begin{bmatrix}\cos(\theta) & -d\sin(\theta)\\ \sin(\theta) & d\cos(\theta)\\ 0 & 1\end{bmatrix}. \tag{8}$$

where v = maximum linear velocity ($|v| \leq v_{\max}$).

ω = angular velocity ($|\omega| \leq \omega_{\max}$) at the point, P, along longitudinal axis of the robot.

The kinematic equation is

$$\dot{P} = \begin{bmatrix}\dot{X}_c\\ \dot{Y}_c\\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\cos(\theta) & -d\sin(\theta)\\ \sin(\theta) & d\cos(\theta)\\ 0 & 1\end{bmatrix}\times\begin{bmatrix}v\\ \omega\end{bmatrix}. \tag{9}$$

Three sensors of AMR provide information about distance from obstacle to calculate absolute distance, d, left angle, θ_l and right angle, θ_r.

Robot maneuvers left turn, $\theta_l>\theta_r$.

Robot maneuvers right turn, $\theta_l<\theta_r$.

Robot maneuvers either left or right turn, $\theta_l=\theta_r$.

4 Fuzzification

Fuzzy logic technique plays significant role in the field of AI, which is one of the methods proposed for decision making applied for AMR. Based on the position and shape of the obstacle, a set of rules are generated and controller select the best rule among.

Experimental AMR considered four inputs for fuzzy controller, i.e., obstacle distances: Front side, d, left side, d_1, right side, d_2, of AMR, and the target angle, α.

Fuzzy controller regulates velocity of right and left wheels of AMR, as in Fig. 5. Triangular shape of membership functions are generated between inputs and outputs.

4.1 Inference mechanism

AMR is designed for target seeking and obstacle avoidance using fuzzy interface device which generates rules against the inputs/outputs. Microcontroller of AMR formulates 48 number of rules with necessary membership functions as shown in Table 1. The generation of rules in fuzzy technique makes ease decision making for navigation with obstacle avoidance.

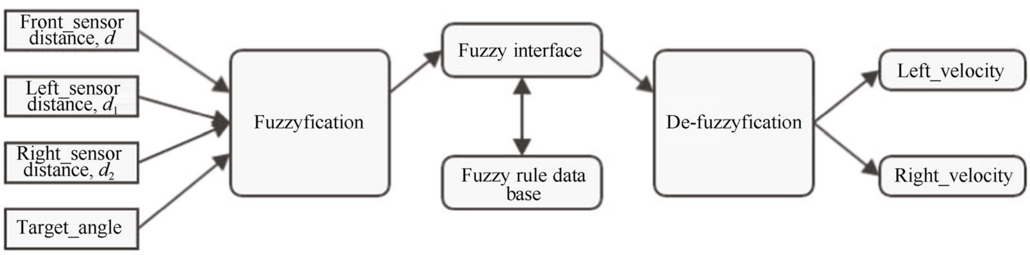


Fig. 5 Schematic process of fuzzy logic controller of AMR

Table 1 Interface rules in fuzzy technique

Fuzzy-rule no (#)	Front-sensor distance (d_1)	Left-sensor distance (d_1)	Right-sensor distance (d_2)	Target-angle (α)	Left-wheel velocity ($Vel._L$)	Right-wheel velocity ($Vel._R$)
1	long	short	middle	negative	slow	quick
2	long	short	long	zero	quick	slow
3	long	short	short	negative	slow	quick
4	middle	middle	short	negative	slow	quick
5	middle	short	long	positive	quick	slow
6	middle	short	middle	negative	slow	quick
7	middle	short	short	negative	slow	quick
8	short	middle	middle	zero	quick	slow
9	short	middle	middle	zero	quick	slow
10	short	short	long	positive	quick	slow
11	short	short	middle	positive	quick	slow
12	short	short	short	positive	quick	slow
13	long	long	short	zero	middle	middle
14	long	middle	short	zero	middle	quick
15	middle	long	short	zero	middle	quick
16	short	long	middle	zero	middle	middle
17	short	long	short	zero	slow	slow
18	short	middle	long	zero	quick	middle
19	long	long	long	positive	quick	slow
20	long	long	long	negative	slow	quick
21	long	long	short	negative	slow	quick
22	short	long	long	positive	quick	slow
23	long	short	short	negative	slow	quick
24	short	short	long	positive	quick	slow
25	middle	short	long	zero	quick	middle
26	long	short	long	zero	quick	quick
27	short	short	long	zero	quick	quick
28	short	middle	middle	zero	quick	middle
29	long	short	middle	zero	quick	slow
30	middle	short	middle	positive	middle	quick
31	short	short	middle	negative	middle	slow
32	middle	middle	short	negative	middle	quick
33	middle	middle	short	positive	middle	quick
34	long	short	short	negative	quick	slow
35	middle	short	short	positive	quick	quick
36	short	short	short	positive	slow	slow
37	short	long	long	negative	slow	quick
38	long	long	long	negative	quick	slow
39	short	long	long	positive	slow	quick
40	long	long	short	negative	quick	quick
41	short	short	long	positive	slow	slow
42	long	short	short	negative	quick	quick
43	short	short	middle	zero	slow	quick
44	short	short	short	negative	slow	slow
45	long	long	short	negative	quick	slow
46	long	middle	short	positive	slow	slow
47	middle	long	short	negative	slow	slow
48	short	long	middle	negative	quick	slow

5 Neural network technique for navigation of AMR

Inquisitiveness in neural networks directs the way of brain functions of human which construct machines to perform intelligent tasks. As in fuzzy system four inputs, distances and target angle with their corresponding output are considered in the method of back propagation neural network (BPNN). For this training, four layered model with two hidden layers, consisting of the sigmoid transfer function, with four input and two output neurons, as shown in Fig. 6.

The above model is trained with the weights through back propagation neural network (BPNN) technique, as in (10)

$$F = \frac{1}{N}\sum_{1}^{N}(e)^2. \tag{10}$$

Weights are adjusted and the network will be trained with given input/output conditions. The trained network is tested under various input conditions like different environments.

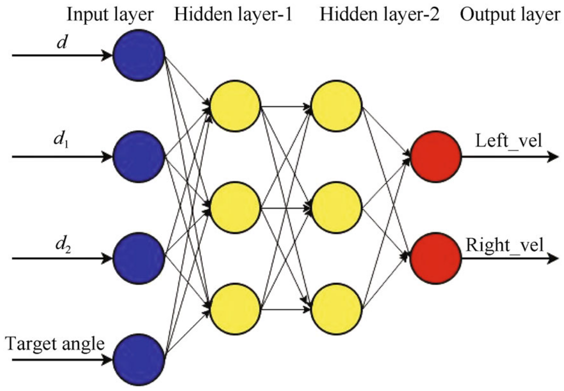


Fig. 6 Architecture of nested neurons in BPNN

6 Adaptive neuro fuzzy inference system (ANFIS)

Even though fuzzy technique delivers good result in decision making, it has lack of human expert control.

The above draw back can be overcome with ANFIS controller, which is a hybrid structure of fuzzy and NN techniques.

ANFIS integrates ideology of fuzzy and neural networks and acquires benefits together in a single framework. Generation of smooth membership functions lead to better decision making in ANFIS technique.

Input layer consists of 4 neurons, first neuron represents, front sensor distance, d. Second neuron for left sensor distance, d_1. Third neuron for right sensor distance, d_2. And fourth neuron corresponds to target angle, α.

First, hidden layer consists of 12 neurons which classify each of input variables into four fuzzy sets by using membership functions. Second, hidden layer comprises of 48 neurons such that every neuron corresponds to a particular fuzzy rule and further calculates its progress. Third, hidden layer labeled as normalized layer, which enfolds 48 neurons, each one computes the corresponding normalized weight. The outputs, S_i with i varying from 1 to 48, in the following equation

$$S_i = \frac{WT_i}{\sum_{i=1}^{48} WT_i}. \tag{11}$$

Fourth hidden layer includes 48 neurons, which is used to determine the consequences of the rules, f_i is calculated at each neuron with (12)

$$f_i = S_i(p_i \times d + q_i \times d_1 + r_i \times d_2 + s_i \times \alpha) \tag{12}$$

where p_i, q_i, r_i and s_i represent the consequent parameters

d = Front sensor distance

d_1= Left sensor distance

d_2= Right sensor distance

α = Target angle.

Output layer includes a single neuron, which calculates the output of ANFIS with subsequent (13)

$$Output = \sum_{1}^{48} f_i. \tag{13}$$

Training in ANFIS is considered in two steps. First is to compute the consequent parameters using algorithm with least square method by keeping parameters of membership functions as fixed.

Second is to calculate membership functions parameters using back propagation neural network technique by maintaining consequent parameters fixed.

The input parameters are separated into four fuzzy logic sets by generalized bell-shaped membership function, as

$$F_n(x,a,b,c) = \frac{1}{1+\left|\frac{x-c}{a}\right|^{2b}}. \tag{14}$$

These results will make membership functions (Fig. 7) as smooth shaped curve, which leads to better navigation of AMR in collision free environment.

7 Discussions of result

The proposed AMR is tested for collision free navigation in various environmental conditions and the difference between simulated and experiment path is shown in Fig. 8.

Generated rules are applied for smooth navigation in different environmental conditions. The experimental results are taken considering the AMR navigation in various environments, as in Fig. 9.

Detailed time based comparison evaluation is made between the three techniques (fuzzy, BPNN and ANFIS) integrated with safe boundary algorithm and the results are plotted in Fig. 10.

Among the applied decision making techniques, the adaptive neuro-fuzzy inference system (ANFIS) with safe boundary algorithm has taken least time to reach the goal.

In addition, the difference of time taken is found less, when AMR is overcoming curved shape obstacles as in Fig. 10 (Environment-3). Hence, ANFIS with SBA technique is most suited especially for contour shape obstacles.

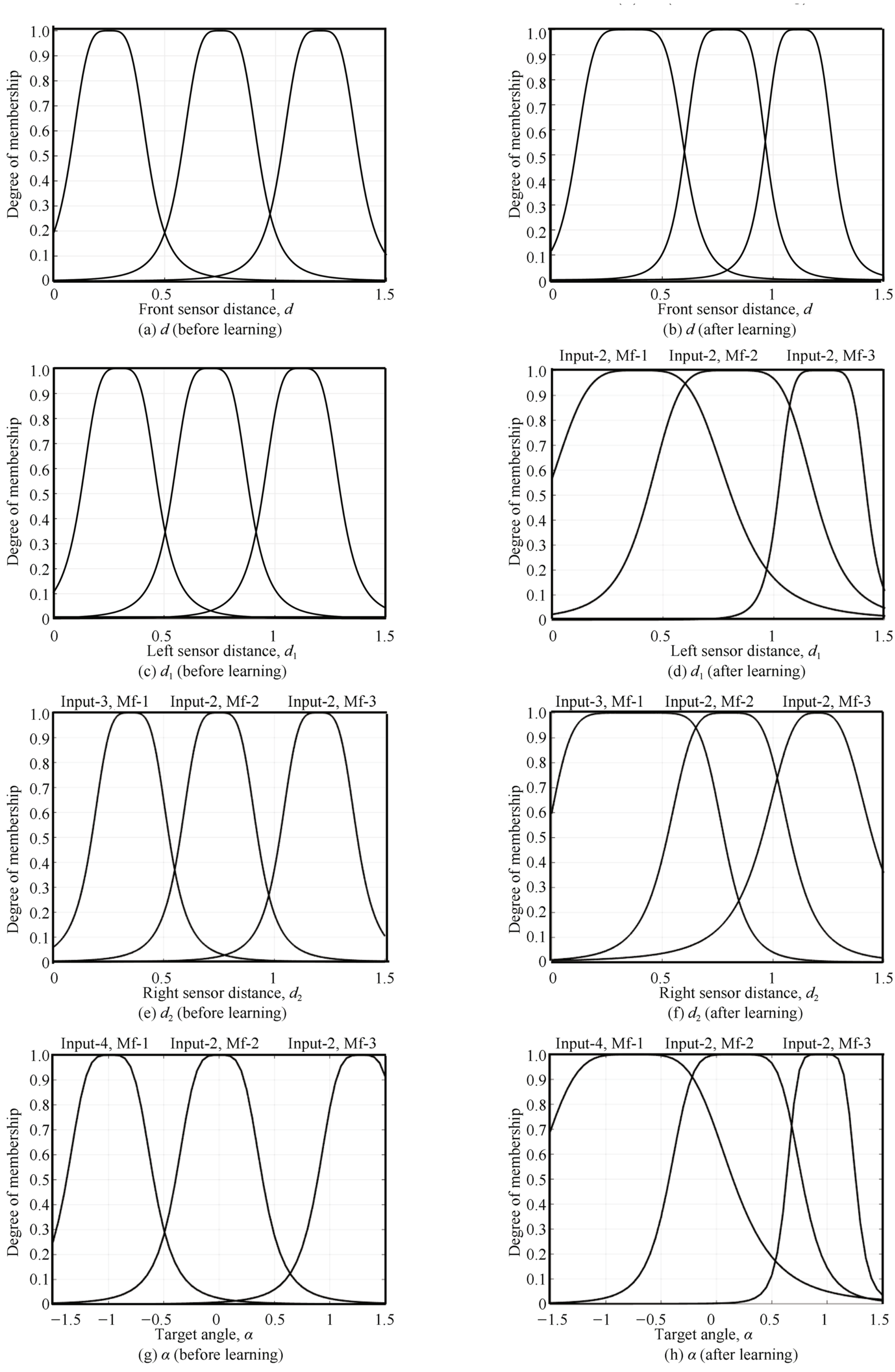


Fig. 7 Membership functions

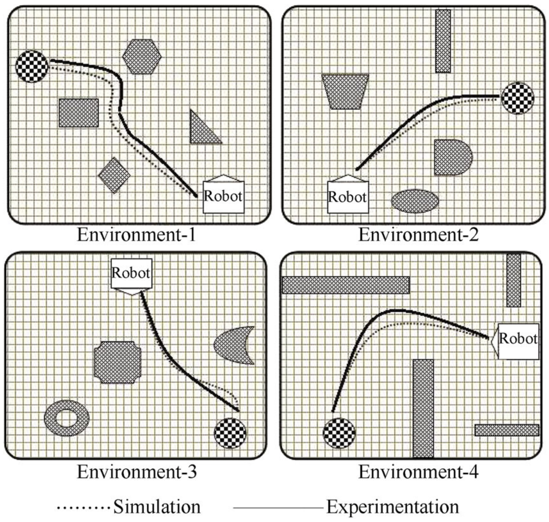
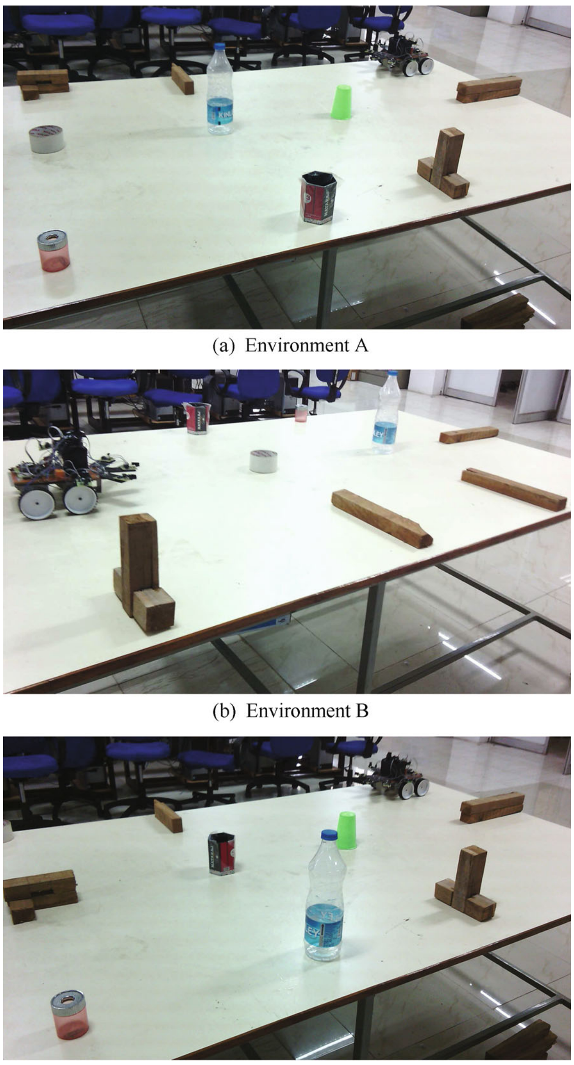


Fig. 8 Robot navigation in various environments



(a) Environment A

(b) Environment B

(c) Environment C

Fig. 9 Experimental navigation of AMR

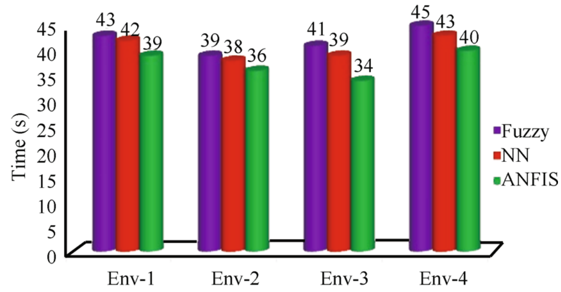


Fig. 10 Time versus environment

8 Conclusions

Among all these cases, ANFIS technique with Safe Boundary Algorithm is most suited for navigation of autonomous mobile robot (AMR), against curved/irregular obstacles, as shown in Tables 2 and 3.

Table 2 Navigation time difference between ANFIS and other modules

Environment	Obstacle shape	Time difference (s)
1	Sharp edges	4.00
2	Sharp/curved edges	3.00
3	Curved/irregular	7.00
4	Sharp edge/blocks	5.00

Table 3 Deviation of experimental path over simulated path

Environment	Deviation (mm)	Relative error (%)
1	3.0	100.00
2	2.0	33.33
3	1.5	0.00
4	3.0	100.00

The graph (Fig. 11) represents that, velocity of AMR is improved, with a maximum of 3.7 % among various modules like Fuzzy, BPNN and ANFIS.

In addition, overall cost of manufacturing of AMR is also moderate. Hence, the proposed AMR programmed with ANFIS included with safe boundary algorithm is robust and will serve the public by giving food and medicines in various circumstances like earthquakes, fire hazards and train accidents.

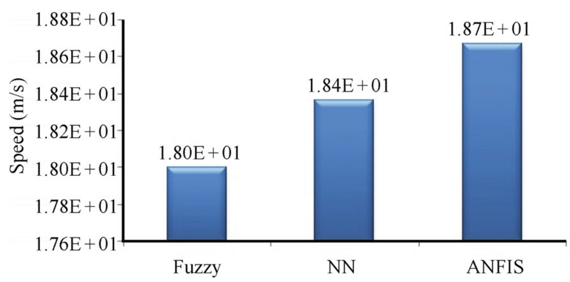


Fig. 11 Robot navigation in various environments

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A. Mallikarjuna Rao received the B. Tech. degree in mechanical engineering from Acharya Nagarjuna University, India in 1999, and the M. Eng. degree in computer aided design/computer aided manufacturing (CAD/CAM) from Andhra University, India in 2004. He currently is a Ph. D. degree candidate navigation of mobile robots, at Andhra University, India. He is working as an assistant professor in Department of Mechanical Engineering, V R Siddhartha Engineering College, Vijayawada, A.P, India.

His research interests include robotics, mechatronics, artificial intelligence, CAD/CAM and additive manufacturing. In particular, his area of research is navigation of autonomous mobile robot using soft computing techniques. In addition, he is also interested to apply various optimizing techniques in additive manufacturing.

E-mail: amrao9@gmail.com (Corresponding author)
ORCID iD: 0000-0003-1805-3883

K. Ramji received the B. Eng. degree in mechanical from Andhra University, India in 1991, the M. Eng. degree in machine design, from Andhra University, India in 1991, the M. Tech. degree in nano technology, from Andhra University, India in 2007. He received the Ph. D. degree in vehicle dynamics, from Indian Institute of Technology, India in 2007. He is working as a professor in Department of Mechanical Engineering, A.U. College of Engineering, Andhra University, Visakhapatnam, India. He has published about 144 refereed journal and conference papers. He completed 15 sponsored research projects funded by various organizations like, University Grants Commission (UGC), Department of Science and Technology (DST), Naval Science and Technological Laboratory (NSTL).

His research interests include vehicle dynamics, type mechanics, finite element method (FEM), CAD, machine design, robotics, mechanisms, signal processing, condition monitoring and nano-technology.

E-mail: ramjidme@gmail.com

B. S. K. Sundara Siva Rao received the B. Tech. degree in mechanical engineering from Andhra University, India in 1974, the M. Tech. degree in machine design, from Andhra University, India in 1978, the Ph. D. degree in static behaviour of shells, from Indian Institute of Technology, India in 1991. He is retired professor in Department of Mechanical Engineering, A. U. College of Engineering, Visakhapatnam, India. He published many journal and conference papers in the area of condition monitoring, fault diagnostics, signal processing etc.

His research interests include machine design, vibration analysis and condition monitoring.

E-mail: bsk_sundara@yahoo.co.in

V. Vasu received the B. Tech. degree in mechanical engineering from Nagarjuna University, India in 1999, the M. Eng. degree in manufacturing engineering from Birla Institute of Technology, India in 2003, and the Ph. D. degree in nano materials, from Jawaharlal Nehru Technical University, India in 2010. He is working as an assistant professor in Department of Mechanical Engineering, National Institute of Technology-Warangal, India.

His research interests include mechatronics, manufacturing engineering, nano-materials, nano-fluids.

E-mail: vvvasu@gmail.com

C. Puneeth received the B. Tech. degree in mechanical engineering from Acharya Nagarjuna University, India in 2011, and M. Tech. degree in CAD/CAM from Jawaharlal Nehru Technical University, Kakinada, India in 2014.

His research interests include robotics and mechatronics. He was interested to develop social autonomous mobile robots with low cost.

E-mail: puneeth66@gmail.com