Dynamic Motion Planning for Autonomous Wheeled Robot using Minimum Fuzzy Rule based Controller with Avoidance of Moving Obstacles

Akhilesh Kumar Tiwari, Arnab Guha, Anish Pandey

Abstract: In this article, the Minimum Fuzzy Rule-Based (MFRB) sensor-actuator controller has designed for dynamic motion planning of a differential drive wheeled robot among the moving, non-moving obstacles and goal in two-dimensional environments. The ring of ultrasonic sensors and infrared sensors have been attached on the front side, left side, and right side of the wheeled robot, which detects the moving obstacles, as well as non-moving obstacles in any environment. This proposed MFRB sensor-actuator controller helps the wheeled robot to move safely in a different scenario. The onboard sensor interpretation data are fed as input to the MFRB controller, and the MFRB controller provides the Pulse Width Modulation (PWM) based wheel velocity commands to both the left and right motors of a wheeled robot. In the numerical simulation and experiment, we have taken one condition that the speed of wheels of the differential drive wheeled robot is at least more than or equal to the rate of the moving obstacles and the moving goal. The numerical simulations are performed through a MATLAB graphical user interface (GUI), and we have used the differential drive wheeled robot to conduct experiments. The presented numerical simulation and experimental results illustrate that the MFRB controller operated wheeled robot has successfully avoided the stationary and non-stationary obstacles in various scenarios.

Keywords: Minimum Fuzzy Rule-Based Controller, Sensor, Actuator, Motion Planning, Wheeled Robot.

I. INTRODUCTION

The application and uses of domestic wheeled robots are increasing day by day. Nowadays, the domestic wheeled robots are doing various works such as floor-cleaning, cloth washing, food serving, pick and place of things, luggage, and goods, etc. Therefore, an automated wheeled robot is required, which can do these types of tasks autonomously.

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* Correspondence Author

Akhilesh Kumar Tiwari, School of Mechanical Engineering, KIIT Deemed to be University, Patia, Bhubaneswar, Odisha, India. Email: akhilesh.tiwarifme@kiit.ac.in

Arnab Guha, School of Mechanical Engineering, KIIT Deemed to be University, Patia, Bhubaneswar, Odisha, India. Email: 1512041@kiit.ac.in

Anish Pandey*, School of Mechanical Engineering, KIIT Deemed to be University, Patia, Bhubaneswar, Odisha, India. Email: anish.pandeyfme@kiit.ac.in

Many artificial intelligence and nature-inspired methods such as Hybrid Fuzzy Controller [1], Neural network Technique [2], Neuro-fuzzy Controller [3], Adaptive Neuro-fuzzy (ANFIS) [4], Simulated annealing algorithm (SA) [5], Particle swarm optimization (PSO) algorithm [6], Genetic algorithm (GA) [7], and Ant colony optimization algorithm (ACO) [8] have been designed and implemented by researchers for wheeled robot motion planning and static/dynamic collision avoidance. Most of the researchers [2, 4, 6-8] have focused on static or non-moving obstacle avoidance based motion planning. However, few of them [1, 3, 5] have considered dynamic or moving obstacles for navigation and obstacle avoidance. In the article [3], the authors have developed the adaptive neuro-fuzzy sensor-based navigation and control system for swarm wheeled robots in unknown static environments. In their work, they have used 48-Fuzzy rules with two behaviours, namely goal searching and collision avoidance. A nature-inspired based simulated annealing algorithm has been applied by Miao and Tian [5] for wheeled robot navigation in different dynamic environments. Ahmadzadeh and Ghanavati [6] have solved the multiple wheeled robots motion planning and control problem by applying the PSO algorithm. Algabri et al. [9] have proposed a fuzzy method with the combination of GA and PSO to improve the navigation and obstacle avoidance strategy of the wheeled robot. Alonso-Mora et al. [10] have implemented a modern optimization method for multiple wheeled robot navigation control and path minimization between moving obstacles. In the article [11], authors have presented a literature survey of various classical and recent soft-computing techniques, which are used for obstacle avoidance and wheeled robot navigation. Position stabilization of a wheeled robot has been done in the article [12].

Motivated by the literature survey as mentioned above, the main objective of this manuscript is to solve the navigation, dynamic and static obstacles avoidance problem of an autonomous differential drive two-wheeled robot in the different working environments. And for this purpose, authors have developed and applied a MFRB sensor-actuator controller. The remainder of the manuscript has arranged as follows: Section 2 presented the problem formulation of dynamic obstacles and goal.

Section 3 describes the implementation of a MFRB sensor-actuator controller for moving obstacle avoidance. The numerical simulation results and their discussion in various scenarios are listed in Section 4. Section 5 illustrates the brief description of the experimental model of a wheeled robot and its outcome for validating the authenticity of the developed MFRB controller. Finally, the conclusion and its future scope of present research work are presented in the Section 6.

II. MOVING OBSTACLES AND GOAL PROBLEM FORMULATION

This section presents the numerical and kinematic modeling (see Figure 1) of differential drive whleeled robot motion and its obstacle avoidance strategy between moving goal dynamic conditions. In Figure 1, X_n is the initial location, and X_{n+1} is the updated location of the wheeled robot on the X-axis. Similarly, Y_n is the initial location, and Y_{n+1} is the updated location of the wheeled robot on the Y-axis. The relationship between the initial location and the updated location of the wheeled robot is given in equations 1 and 2. The angle α represents the turning angle of the wheeled robot about the X-axis, which is changing according to the position of goal point (see equation no. 3). The velocity 'V' of the wheeled robot is calculated in equation 4, which varies according to the wheel diameter 'd' of robot and the 'N' angular speed of wheel motors in RPM (Revolutions Per Minute). In the present study, the minimum and maximum velocities vary from 0.067 m/sec to 0.167 m/sec, which is adjusted by the PWM control signal of motors. In Figure 1, G_{X_n} is the starting positions, and $G_{X_{n+1}}$ is the updated positions of the moving goal in the X-axis. Similarly, G_{Y_n} is the starting positions, and $G_{Y_{n+1}}$ is the updated positions of the moving goal in the Y-axis. The goal is started moving from the top to bottom with the angle Φ. If the robot touches the goal, then the robot and goal both are stopped moving forward. In Figure 7 (see the simulation section), D_{1X_1} and D_{2X_1} are the starting positions, and $D_{1X_{n+1}}$ and $D_{2X_{n+1}}$ are the updated positions of the first and second moving obstacles in the X-axis. Similarly, D_{1Y_1} and D_{2Y_1} are the starting positions, and $D_{1Y_{n+1}}$ and $D_{2X_{n+1}}$ are the updated positions of the first and second moving obstacles in the Y-axis. In the simulation Figure 7, the first moving obstacle is started travelling from right to left with the angle of θ, and the second moving obstacle is started travelling from left to right with the angle of θ.

The kinematic equations for navigation and static and dynamic obstacle avoidance of a wheeled robot is given below: -

$$X_{n+1} = X_n + V \times \cos\alpha \qquad (1)$$

$$Y_{n+1} = Y_n + V \times \sin\alpha \qquad (2)$$

$$\alpha = \tan^{-1}\left[\frac{G_Y - Y_{n+1}}{G_X - X_{n+1}}\right] \qquad (3)$$

$$V = \frac{\pi \times d \times N}{60} m/sec \qquad (4)$$

$$D_{1X_{n+1}} = D_{1X_1} - (0.8 \times \cos\theta) \qquad (5)$$

$$D_{1Y_{n+1}} = D_{1Y_1} - (0.8 \times \sin\theta) \qquad (6)$$

$$D_{2X_{n+1}} = D_{2X_1} + (0.8 \times \cos\theta) \qquad (7)$$

$$D_{2Y_{n+1}} = D_{2Y_1} + (0.8 \times \sin\theta) \qquad (8)$$

$$\theta = 2^\circ \qquad (9)$$

$$G_{X_{n+1}} = G_{X_n} - (0.2 \times \cos\phi) \qquad (10)$$

$$G_{Y_{n+1}} = G_{Y_n} - (0.2 \times \sin\phi) \qquad (11)$$

$$\phi = 186^\circ \qquad (12)$$

where n = 0, 1, ……n

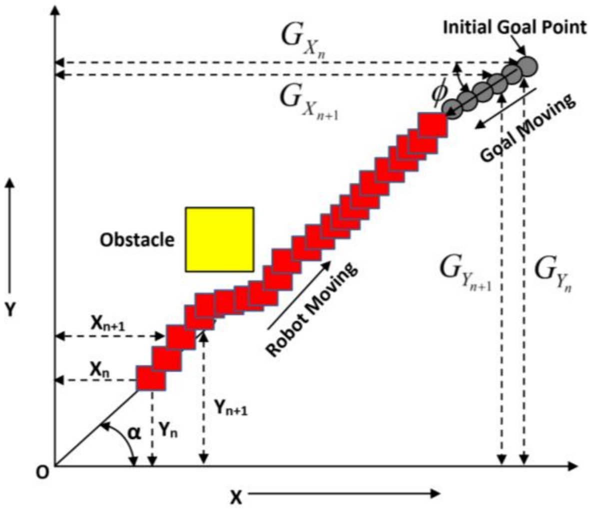

Fig. 1.Kinematic motion study of differential drive wheeled robot between static obstacle and moving goal in the workspace.

III. DESIGN OF MFRB SENSOR-ACTUATOR CONTROLLER FOR MOVING OBSTACLE AVOIDANCE

This section presents the design and implementation of a MFRB sensor-actuator controller for dynamic motion planning and collision avoidance strategy of differential drive wheeled robot. This proposed MFRB controller will be used in the numerical simulations and experiment modes to control the wheel speeds of the robot by sensor data interpretation. The controller collects the input, i.e., nearest forward (minimum) static and dynamic obstacles distance from the different sensors. And the controller provides the right and left wheel velocity controlled command to the motors of wheels of the robot through PWM signal, which varies from 0 to 255, that means low (minimum) to high (maximum) polarity of the motor speed. The two Gaussian type membership variables are chosen for input and outputs. The basic structure of the Gaussian membership function is depicted in Figure 2. The range of input is divided into two linguistic variables: Near and Away, respectively (see Figure 3 (a)), which are located between 20 cm to 80 cm in membership values of the Y-axis. Similarly, the range of outputs is partitioned into two linguistic variables, namely Low and High, respectively (see Figure 3 (a, and b)). The minimum fuzzy rule sets of the MFRB controller are listed in Table 1. The general structure of an MFRB controller for velocity control of the wheeled robot is illustrated in Figure 4.

The expressions of MFRB controller are derived through Mamdani-type If-Then fuzzy model in the following form: -

Rule No. 1: If Closest Front Obstacle is Far Then the Right Wheel Motor PWM (RWPWM) is Maximum and Left Wheel PWM (LWPWM) is Maximum.

Rule No. 2: If Closest Front Obstacle is Close Then the RWMPWM is Minimum and LWPWM is Maximum.

Rule No. 3: If Closest Front Obstacle is Close Then the RWPWM is Maximum and LWPWM is Minimum.

The description of the name of the membership function of Input and Outputs is given below: -

Closest or Nearest Forward Obstacle (CFO) = {CLOSE (Near), FAR (Away)}

RWPWM = {MINIMUM (Low), MAXIMUM (High)}

LWPWM = {MINIMUM (Low), MAXIMUM (High)}

The fuzzy set has a Gaussian membership function, which is mentioned below: -

$$\mu_{ij}\left(x_j;c,\sigma\right) = \exp\left[-\frac{1}{2}\left(\frac{x_j - c_{ij}}{\sigma_{ij}}\right)^2\right] \tag{13}$$

where i =1…3 (three rules) and j = 1 (single input variable), the c_{ij} and σ_{ij} are tuning parameters of the membership function, known as centre and width, respectively.

The defuzzification of the outputs (RWPWM and LWPWM) are calculated by the weighted average method: -

$$RWPWM = \frac{\sum_{i=1}^{3}\left(\mu_{ij}\left(x_j;c,\sigma\right)\right)\cdot RWPWM}{\sum_{i=1}^{3}\left(\mu_{ij}\left(x_j;c,\sigma\right)\right)} \tag{14}$$

$$LWPWM = \frac{\sum_{i=1}^{3}\left(\mu_{ij}\left(x_j;c,\sigma\right)\right)\cdot LWPWM}{\sum_{i=1}^{3}\left(\mu_{ij}\left(x_j;c,\sigma\right)\right)} \tag{15}$$

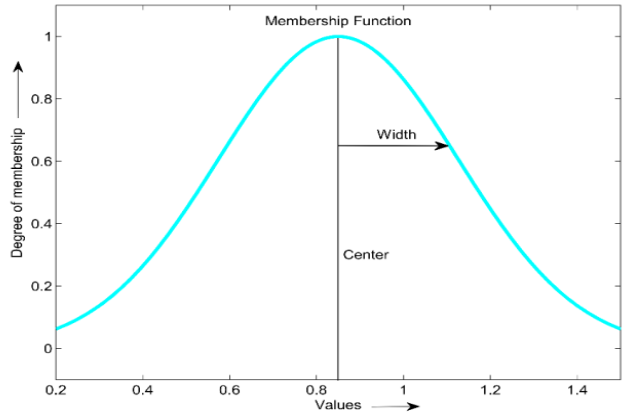

Fig. 2.The basic structure of the Gaussian membership function.

Table- I: The minimum fuzzy rule set of the MFRB controller

If-then Rule No.	Closest (Minimum) Front Obstacle	RWPWM	LWPWM
1.	Far (Away)	Maximum (High)	Maximum (High)
2.	Close (Near)	Minimum (Low)	Maximum (High)
3.	Close (Near)	Maximum (High)	Minimum (Low)

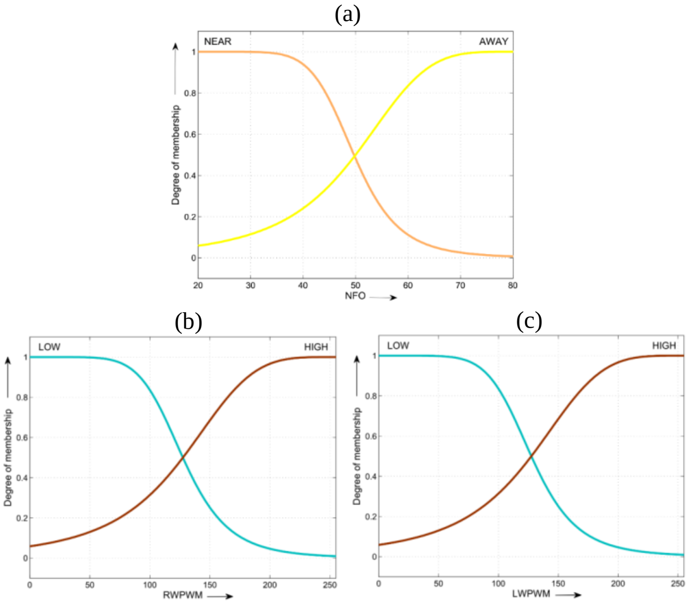

Fig. 3. Fuzzy membership functions of Input (CFO) and Outputs (RWPWM and LWPWM).

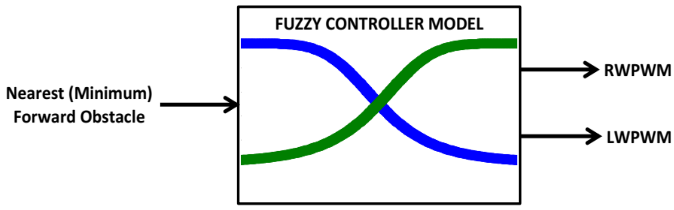

Fig. 4. The general structure of an MFRB controller for right and left wheel velocity control.

IV. RESULTS AND DISCUSSION ON COMPUTER SIMULATION

Various complex environments filled with static obstacles, moving obstacle, and goals have been taken to show an autonomous motion and orientation of a wheeled robot by applying an MFRB sensor-actuator rule base controller. A GUI model of MATLAB software has been used for the demonstration of computer simulations for a wheeled robot. In this GUI model, we have randomly placed the obstacles and during the motion of a wheeled robot, the robot finds obstacles in front of it. We pretend that the wheeled robot runs with the velocity, which must be greater than or equal to the velocity of the hindrances and targets. Fuzzy model is claiming an easy route by employing sensor-based native data on the complex dynamic environment. Further, various simulations have been performed by applying the proposed technique, which is described below: -

A. Fixed Hindrance and Dynamic Target Simulation

Wheeled robot is navigated in the environment, having fixed obstacle and dynamic target and have been presented in this section.

It is to be presumed that the trajectory for a wheeled robot to reach the target is obscure. Figure 5 explains that the wheeled robot arrives at the moving target because the velocity of a wheeled robot is more than the speed of the target point.

The positions of fixed hindrance and a dynamic target is listed in Table 2. Fuzzy model is claiming an easy route by employing sensor-based native data on the obscure dynamic environment.

Table- II: Simulation status of fixed hindrance and dynamic target

Robot Initial Location	**(X_n, Y_n) = (50 cm, 50 cm)**
Fixed Hindrance Location	**(Obs(X), Obs(Y)) = (200 cm, 100cm)**
Movable Target Initial Location	(G_{X_n}, G_{Y_n}) **= (700cm, 180cm)**
Target turning Angle	**ϕ = 185°**

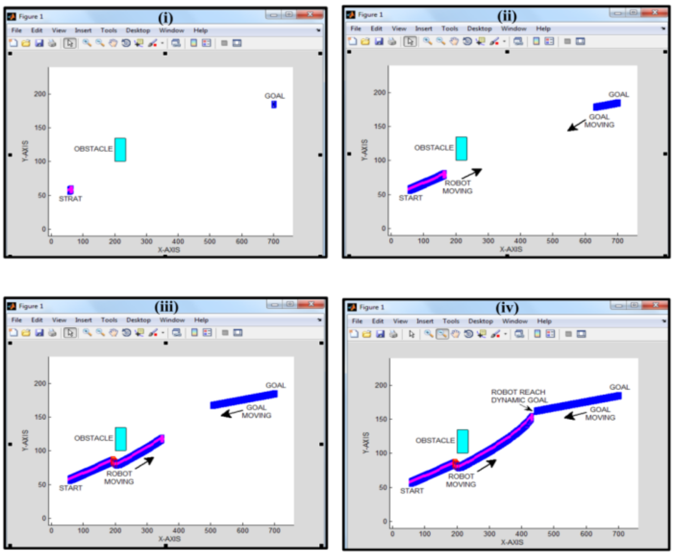

Fig. 5.Motion of wheeled robot in a dynamic scenario with fixed hindrance and movable goal.

B. One Movable, One Fixed Hindrance and Fixed Target Simulation

Figure 6 shows that the wheeled robot is shunning the movable as well as fixed obstacle and reaching the target by selecting the smooth trajectory. Wheeled robot navigation in movable hindrance is shown in Figure 6. The robot is initiated from the location (10cm, 10cm). The moving hindrance is initially located at the (220cm, 100cm) and moving to the position (5cm, 100cm) in the right to left direction (see Table 3). Simulation results show the following situations: -

1. When the obstacle is not near to the robot.

The velocity of both wheels remains same, and the robot moves forward.

2. When an obstacle is near to be a wheeled robot.

The velocity of the right wheel of the robot reduced, and the robot turn right to save the collision with the hindrance.

Table- III: Simulation status of one movable, one fixed hindrance and Fixed Target

Robot Initial Location	**(X_n, Y_n) = (10 cm, 10 cm)**
Movable Hindrance Initial Location	(D_{1X_1}, D_{1Y_1}) **= (220 cm, 100 cm)**
Fixed Hindrance Location	**(Obs(X), Obs(Y)) = (160 cm, 150 cm)**
Hindrance Turning Angle	**θ = 2°**
Fixed Target Location	**(T_X, T_Y) = (200cm, 200cm)**

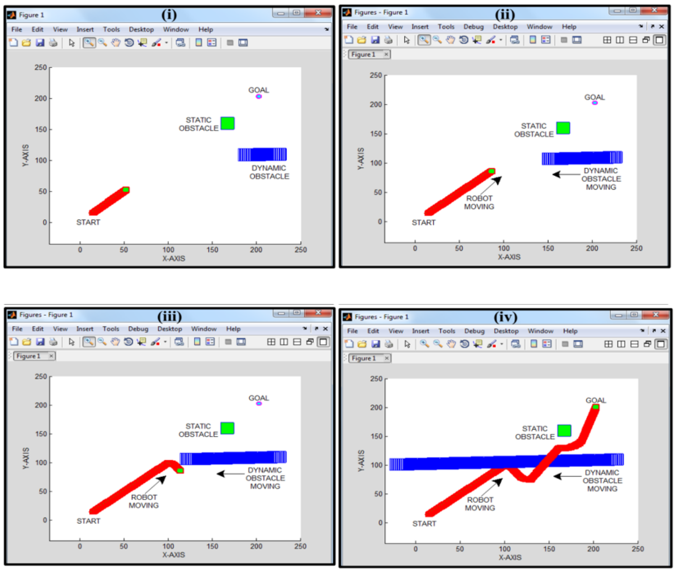

Fig. 6.Motion of wheeled robot in a dynamic condition with one moving, one fixed hindrance and fixed target.

C. Two Movable Hindrance and Fixed Target Simulation

Environment used in this case contains two movable hindrances and fixed target. Wheeled robot navigation is introduced in this environment. The wheeled robot is unaware of the trajectory of the movable hindrances. Figure 7 describes the movement of first and second movable obstacles are from right to left and from left to right, respectively. The positions two movable hindrances and the fixed target is listed in Table 4. Fuzzy model is claiming an easy route by employing sensor-based native data on the obscure dynamic environment.

Table- IV: Simulation status of two movable hindrances and fixed target

Robot Initial Location	**(X_n, Y_n) = (10 cm, 10 cm)**
Movable Hindrance Initial Location	(D_{1X_1}, D_{1Y_1}) **= (220 cm, 100 cm)** (D_{2X_1}, D_{2Y_1}) **= (0 cm, 150 cm)**
Hindrance Turning Angle	**θ = 2°**
Fixed Target Location	**(T_X, T_Y) = (200cm, 200cm)**

D. Fixed Hindrance and Fixed Target Simulation

This case describes the motion and orientation of a wheeled robot in a complicated environment, where robot and target are located at the opposite quandary. Simulation results (see Figure 8) shows the following situations: -

1. When an obstacle is not near to the robot.

The velocity of both wheels remain the same, and the robot moves forward toward the target.

2. When the obstacle is near to be robot.

The velocity of the left wheel of the robot reduced, and the robot turn left to save the collision with the hindrance and reach the target successfully. The shortest and best path has been selected by the robot autonomously from the outputs of MFRB sensor-actuator controller. Table 5 shows the positions of various obstacles present in the environment, which are avoided by the wheeled robot to reach the target.

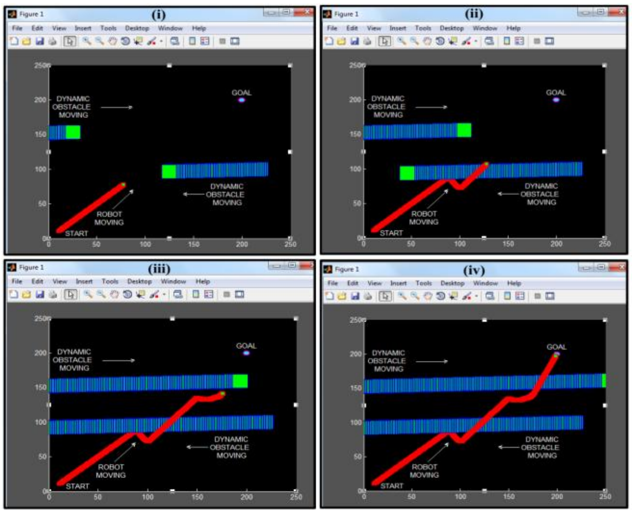

Fig. 7.Motion of wheeled robot in a dynamic scenario with two movable hindrances and fixed target.

Table- V: Simulation status of fixed hindrances and fixed target

Robot Initial Location	**(X_n, Y_n) = (130 cm, 70 cm)**
Fixed Hindrance Locations	**$(ObsX_1, ObsY_1)$ = (50 cm, 50 cm)** **$(ObsX_2, ObsY_2)$ = (80 cm, 80 cm)** **$(ObsX_3, ObsY_3)$ = (100 cm, 100 cm)** **$(ObsX_4, ObsY_4)$ = (30 cm, 160 cm)** **$(ObsX_5, ObsY_5)$ = (80 cm, 250 cm)** **$(ObsX_6, ObsY_6)$ = (150 cm, 240 cm)** **$(ObsX_7, ObsY_7)$ = (200 cm, 50 cm)** **$(ObsX_8, ObsY_8)$ = (250 cm, 120 cm)** **$(ObsX_9, ObsY_9)$ = (180 cm, 180 cm)** **$(ObsX_{10}, ObsY_{10})$ = (230 cm, 230 cm)**
Fixed Target Location	**(T_X, T_Y) = (220cm, 280cm)**
Initial Turning Angle (TA)	**$\alpha = 66.77°$**

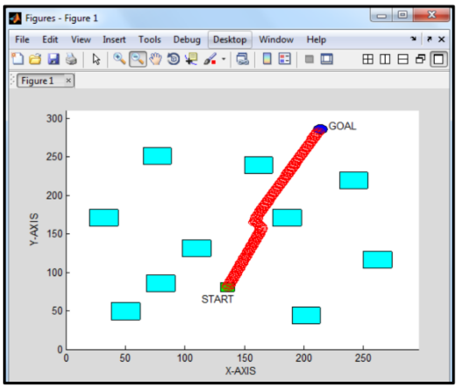

Fig. 8.Motion of wheeled robot in a complicated environment between many fixed hindrances and traget.

V. EXPERIMENTAL RESULTS AND DISCUSSION

A prototype of the wheeled robot is designed for experiments in real situations in the absurd dynamic environment. Figure 9 shows the experimental model of the wheeled robot. Two motor-powered wheels are accompanied with a vehicle-type wheeled robot to control the motion and turning of the robot. A caster wheel is attached at the rear part to balance and it gives easy orientation during motion. Arduino UNO (ATmega328) microcontroller is used in which the MFRB sensor-actuator controller is sent as a C programming language. Sensor delivers the range information to the microcontroller, which further controls the velocity of the right and left wheels PWM. This PWM signal controls the motion and turning of the wheeled robot by controlling the velocity of left and right wheels. It ranging between 0-255, it shows that the motor speed from minimum to maximum polarity, and its equivalent fuzzy values are from low and high.

The two independent wheels are used to control the movement of the wheeled robot in the backward direction, forward direction, and it's turning. The two separate DC geared motors give the power to the wheels. The L298 dual DC motor controller is utilized to adjust the speed of the motors. The motor driver is attached with Arduino UNO (ATmega328) microcontroller. Following conditions are obtained after detecting the obstacle in the path: -

1. No obstacle: Velocity PWM high for both right and left wheels.

2. Obstacle detected at right side: Robot turns left means the PWM value is higher for right wheel and lower for left wheel.

3. Obstacle detected at left side: Robot turns right means the PWM value is higher for left wheel and lower for right wheel.

Two ultrasonic range (UR) finder sensor and one infrared range (IR) sensor is attached with the wheeled robot to detect the nearest moving hindrances close to it. To select the appropriate wheel velocity PWM in absurd dynamic environment, sensors detect the nearest forward hindrance. Figure 10 describes the placement of a sensor mounted on the robot. UR finder sensors are capable of measuring the distance ranging from 2 cm to 400 cm and are attached at the right and left side. The IR sensor measure distance ranging from 20 cm to 150 cm and is attached at the front of the robot. It is also used to detect the bearing of the moving target. Three dissimilar environments are selected for the representation of experiment results in this article; these are described in different figures. Figure 11(a) shows the robot moving in the unstructured environment, and Figure 11(b) shows the environment consists of rectangular-shaped static obstacles. Figure 12(a) shows the environment having a moving obstacle (man) in the path of the robot. Figure 12(b) presents the robot avoided the moving obstacle (man).

Static, as well as moving obstacles, are avoided by using a MFRB sensor-actuator controller wheel velocity PWM motor controller in all absurd environments. With the implementation of on board sensory information, the wheeled robot can quickly inspect and obtain a path to avoid collision with an obstacle is outlined by the experiment result.

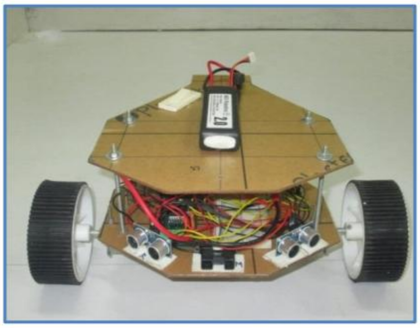

Fig. 9.Prototype of wheeled robot for experiment.

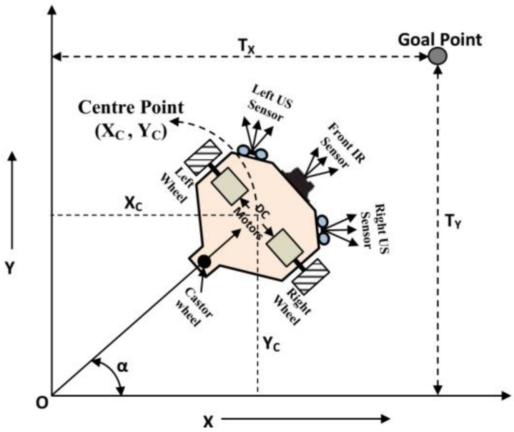

Fig. 10. A two-dimensional model of the wheeled robot kinematics eqipped with three sensors.

Fig. 11. (a) Motion of wheeled robot between an absurd complex environment condition, (b) Navigation in an absurd complicated environment with few fixed hindrances.

Fig. 12. (a) Navigation in an absurd non-stationary environment with a moving man hindrance, (b) Navigation in an absurd dynamic environment avoids themoving man hindrance.

VI. CONCLUSION

In the present article, the MFRB sensor-actuator controller has designed and implemented for dynamic motion planning of a differential drive two-wheeled robot among the moving, non-moving obstacles and goal in different two-dimensional environments. The developed MFRB controller helped the robot to choose a collision-free safe path from one point to another between obstacles. The MFRB controller has mainly worked based on the autonomous sensor-actuator controlled technique. The results of numerical simulation and experimental show that the MFRB controlled wheeled robot has successfully avoided the stationary and non-stationary obstacles and reaches the goal in different situations. In the future, this developed controller can be implemented for multiple wheeled robot navigation and obstacle avoidance.

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AUTHORS PROFILE

Prof. Akhilesh Kumar Tiwari has completed her M. Tech. degree in Production Enginering from IIT Roorkee, Uttarakhand, India in the year of 2017. He has published paper in Various Journal and Conference Proceeding. He has more than two-year experience in teaching and research. Currently, he is working as a Professor (Assistant I) at School of Mechanical Engineering at KIIT Deemed to be University, An Institute of Eminence, Bhubaneswar, Odisha.

M. Tech. Scholar Arnab Guha is doing his M. Tech. degree in Machine Design from KIIT Deemed to be University, An Institute of Eminence, Bhubaneswar, Odisha. He has presented one Conference at ICAMPD-2019.

Dr. Anish Pandey* has completed his Ph.D. degree in mobile robotics from NIT Rourkela, Odisha, India in the year of July 2016. His research interests are in Bio-Inspired (Nature-Inspired) Optimization Methods, Fuzzy Logic, Neural Networks, and Evolutionary Algorithms based Mobile Robot Navigation. He has published many papers in Various Journals, Conference Proceedings and filed two patents. His Google Scholar citations have been 373 with 12 h-index. He has more than three-year Post Ph.D. experience in teaching and research. Currently, he is working as a Professor (Assistant II) at School of Mechanical Engineering at KIIT Deemed to be University, An Institute of Eminence, Bhubaneswar, Odisha.