# Analysis and Investigation of Mamdani Fuzzy for Control and Navigation of Mobile Robot and Exploration of different AI techniques pertaining to Robot Navigation

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**Abstract**— The field of autonomous navigation using robots have seen a lot of research in past few decades due to its increasing demand and application in various sectors. In the current paper Mamdani fuzzy has been analyzed for navigation and control of robot during path planning. During the research simulation and experimental results for path length and time taken from source point to target point have been depicted using the fuzzy methodology. The results are found to be in good agreement. In the current analysis several AI methods have also been studied and their potential for application in the field of robotics have been discussed.

**Keywords**— Mamdani, fuzzy, mobile robot, path planning, navigation, control strategy

## 1 INTRODUCTION

The need of self-governing mobile robots is increasing day by day to replace humans from places where the risk factor is more for human life and to work in harmony in dynamic environments while cooperating with humans. In order to act independently, an autonomous behaviour is to be designed for the robot, making use of various classical and reactive techniques. The mobile robot will face static as well as dynamic surrounding while operating in real time i.e. the obstacles may be stationary or moving or both. The mobile robot should be able to detect the shortest possible path to reach the destination avoiding stationary as well as moving hindrances. The main and most important task in mobile robot navigation is path planning which is categorised as global and local path planning as discussed in [1]. In global path planning the mobile robot is already aware of its surroundings and in local path planning the surrounding environment is unknown to the robot. In both cases the surrounding can be static or dynamic in nature. Static environments are dealt by mobile robot using classical approaches such as road map building techniques, cell decomposition method, potential field methods as presented in [2,3]. Reactive approaches or techniques are utilized for tackling navigation problem in dynamics environments where the obstacles are stationary and moving. [4-8] present various techniques used for tackling problem of navigation in dynamic environment. In papers [9-11], comparison between static path planning and dynamic path planning are presented. Reactive approaches include neural networks, fuzzy logic, neuro-fuzzy, bio-inspired techniques and hybrid techniques.

## 2 PROBABILISTIC USE AND ANALYSIS OF TECHNIQUES FOR MOBILE ROBOT NAVIGATION

In road map building technique a number of paths are constructed in a given environment such that on following any of the path the robot will reach the destination position without colliding with any obstacle. A lot of research had been done in this field and as a result roadmaps have been categorised into two sets as described in [12-16]. In papers [17-19], a novel approach is represented which made use of two types of maps viz. occupancy grid map and topological map utilising features of each type of map and enabling robot to construct roadmap in real time.

Cell Decomposition method is categorized as exact cell decomposition and approximate cell decomposition method as discussed in [20-23]. In exact method, path contains unnecessary turns which are the centre points of cell and making it look abnormal where in approximate method whole space is divided into cell marked with flag denoting its occupancy. Potential field method involves generation of a virtually charged field in the space to be navigated where the navigating body and the target position are provided with opposite type of charge so that it gets attracted to the target position providing target seeking behaviour and navigating body and obstacles are given same charge as a result a repulsive force act between them pushing body away from obstacle providing obstacle avoidance behaviour as presented in [24-28].

Neural Network technique utilizes the concept behind working of the human brain and try to imitate behaviors such as self-learning, recognizing patterns and optimizing a problem. Artificial neurons are created that store information from past experiences in it in form of synaptic weights which are later connected to form a network. Neural networks are categorized on the basis of layer used as single, multiple and competitive and on the basis of training methodology as supervised, unsupervised and self-supervised as discussed in [29-33]. Papers [34-36], use multi-layered neural network which is trained using the input data in form of distance from the laser range finder sensor and is presented to achieve environmental recognition and local navigation behavior. Papers [37-44] discuss the use of dual artificial neural network, probabilistic neural network, MLP and RBF neural network and effect of different activation functions on path planning and navigation of mobile robot. Papers [45-64] describe how these artificial neural network can be used for various engineering problems.

Fuzzy logic is an attempt to mimic human like reasoning ability on the basis of information perceived. Fuzzy logic based navigation controller is discussed in [65] for an autonomous mobile robot. Papers [66-69] help to understand the application of fuzzy logic for different diagnoistic areas. Papers [70-74], present fuzzy logic based controllers for single and multiple robots in complex and jumbled environments. Papers [75-77] present various rule based methods for generation of behaviors like obstacle avoidance, target seeking and wall following by controlling heading angle and different parameters. Papers [78-83] discuss different behavior generation techniques and effect of hybrid membership functions used in fuzzy application. The application of different types of fuzzy models and hybridization of these fuzzy inference system with bio-inspired techniques for better results have been discussed in papers [84-94]. Fuzzy inference systems are widely used for various problems in todays world and some of the applications are depicted in papers [95-106].

Neuro-Fuzzy technique is a hybrid technique which incorporate features of neural networks and fuzzy logic. It derives it learning ability utilizing feature of both neural network and fuzzy logic for enhanced results. Neuro-Fuzzy systems are like multiple neural networks operating parallel to each other and in whole defining a multi-dimensional fuzzy system where neural networks are used for tuning parameters i.e. the membership function for the fuzzy system. System is initially fed with training data and after that it derives a set of rules from that data for further use and keeps on tuning those derived rule for better results. [107-116] discuss the use of ANFIS approach for various applications like robot navigation, path planning. Papers [117-123] present various modifications to the basic neuro fuzzy model for obtaining better results such as re-enacted toughening method, rule based neuro fuzzy, RAM-based neuro fuzzy system, multiple layered neuro fuzzy and Altera Field Programmable Gate Array.

In ANFIS approach, which made use of obstacle distance data from ultrasonic range finder sensor in form of right obstacle distance, front obstacle distance and left obstacle distance as inputs and provide output as the steering angle to avoid collision. A five layered ANFIS was used for obtaining the desired results which were verified using simulations. Another ANFIS based controller which took 4 sensor inputs viz. right obstacle distance, front obstacle distance, left obstacle distance and heading angle. The use of ANFIS for navigation and method to hybridize it with bio- inspired techniques are discussed in [124-136] for fine tuning the results. Papers [137-142] show the application of ANFIS approach for various engineering problems. There are a number of novel approaches which make use on neural network technique for environmental and system diagnosis and are presented in [143-157].

Bio-inspired techniques as the name suggested have been derived from phenomenon occurring in nature like movement of insects specially ants, bees', fireflies etc., growing patterns of weed or the social behavior of animals, immune system of living beings etc. These section of the paper presents a brief introduction of these techniques and their hybridization with other reactive techniques for increasing efficiency. Some of the most commonly used bio-inspired techniques are Genetic Algorithm, Particle Swarm Optimization, Ant Colony Optimization, Firefly Algorithm, Artificial Immune System and Invasive Weed Optimization.

Genetic algorithm is an evolution based optimization techniques which incorporate various action viz. defining fitness function, selection, crossover and mutation which are performed to find the closest optimal solution. [158-160] present an approach for implementing this evolutionary technique for path planning of a mobile robot in dynamic environment in which the defined fitness function accounts for different behaviors of robot for safe navigation. Particle swarm optimization is based on the action and behavior of swarm of animals. Papers [161-165] discuss the utilization of PSO technique for path planning and how the above mentioned technique can be coupled with fuzzy inference system, neural network, neuro fuzzy and other bio-inspired techniques for achieving better navigation. ACO technique is based on movement tactics of an ant inside a colony, [166-169] discuss how environmental information and length of the path are incorporated in a fitness function which is solved using a neural network where each node of the path generated by neural network is treated as an ant. An investigation was done for examining the ideal system of subterranean insect state utilizing swarm insight method and ant colony optimization.

Papers [170-171] dealt with a new motion planning technique based on a biological innate immune system. A new parameter named learning rate was introduced for actuating an environment suited action. Author introduced a straightforward framework for a versatile robot route generation using Artificial Immune System approach in which natural conditions are shown as antigens and arrangement of activity techniques are dealt with as antibodies. A few more bio-inspired techniques are inspired from motion of cuckoo bird, fireflies, bees and based on pollination process in nature. In papers [172-175], a metaheuristic algorithm that is based on the flight behavior and brood parasitic behavior of cuckoos named cuckoo search algorithm is used for generating the optimized path for navigation of mobile robot along with their modified versions. In paper [176], two controllers were designed based on naturally inspired algorithms namely flower pollination algorithm and bat algorithm for calculating optimal path for navigation of mobile robot. FPA used pollination process as observed in nature and BP used echolocation for finding the optimal path.

Approaches like harmony search, invasive weed optimization,

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gravitational search algorithm and simulated annealing are presented in [177-181]. Papers [182-184] show comparision between results obtained for navigation of robot using different hybrid bio-inspired techniques. These bio-inspired techniques can also be used in various engineering domains as shown in papers [185-200]. Papers [201-208] present some more methods such as modified shuffled frog leap algorithm, dynamic differential evolution approach etc for intelligent navigation of an autonomous robot. In order to apply these techniques to the actual robots, first kinematic and dynamic modelling of wheeled robots is done in order to derive differential equation for position, velocity and motion. Papers [209-220] present the kinematic and dynamic modelling of various robots including various mobile manipulators.

## 3 Analysis of Mobile Robot Navigation Using Mamdani Fuzzy Inference System

In this section the application of a Mamdani Fuzzy inference system for navigation of a mobile robot is discussed. The Mamdani Fuzzy inference system used five inputs namely FOD (Front Obstacle Distance), ROD (Right Obstacle Distance), BOD (Back Obstacle Distance), LOD (Left Obstacle Distance) and HA (Heading Angle) using the sensors present in the mobile robot and process these inputs based on various rules incorporated while designing the FLC (Fuzzy Logic Controller) to provide an output i.e. SA (Steering Angle). Inputs used in the above mention method comprise of three types of membership functions namely triangular, trapezoidal and Gaussian where as the output comprise of only Gaussian type membership functions.

### 3.1 Inputs and Output Membership Functions

The value of inputs FOD, ROD, BOD and LOD are in range 0 to 6 meters based on the capability of the sensors on the mobile robot and HA's value is assumed to vary from -180 to +180 degrees as shown in figures below. FOD, ROD, BOD and LOD utilizes trapezoidal, triangular and Gaussian membership functions and fuzzy sets are formed for these inputs as Very_Near, Near, Medium, Far, Ver_Far whereas HA utilize only gausian membership function and fuzzy sets for it are categorized as N*, N, Z, P, P*. The output SA is defined using only Gaussian membership functions and fuzzy set categorization is similar to h eading angle.

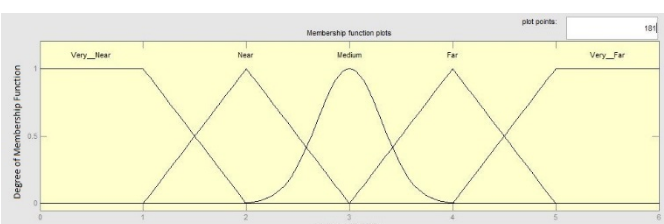


Fig. 1. Input FOD (Front Obstacle Distance)

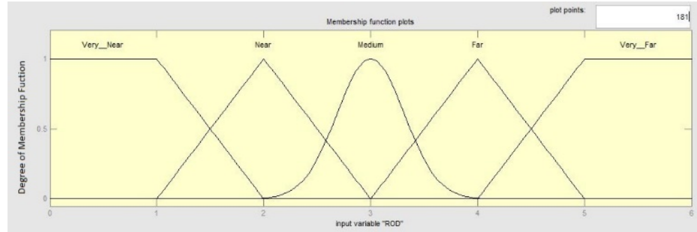


Fig. 2. Input ROD (Right Obstacle Distance)

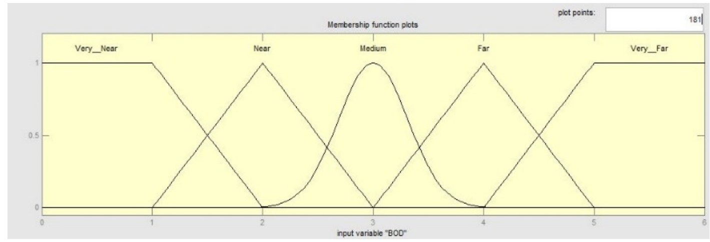


Fig. 3. Input BOD (Back Obstacle Distance)

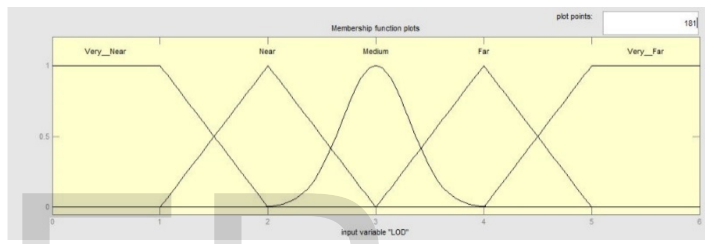


Fig. 4. Input LOD (Left Obstacle Distance)

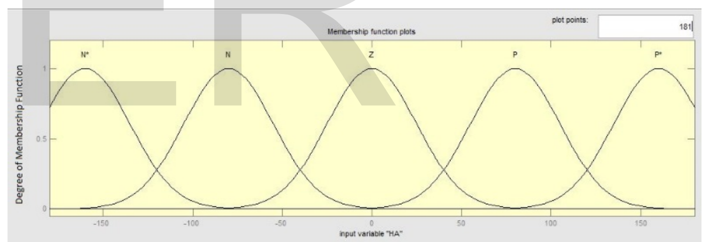


Fig. 5. Input HA (Heading Angle where membership functions are named as N*, N, Z, P, P* in order from negative to positive)

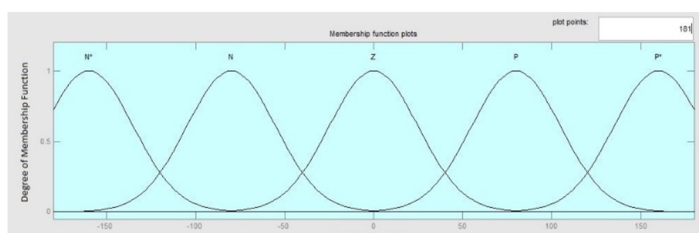


Fig. 6. Output SA (Steering Angle where membership functions are named as N*, N, Z, P, P* in order from negative to positive)

### 3.2 Membership Functions

Mainly three types of membership functions are used in this research viz. triangular, trapezoidal and Gaussian. These membership functions can be mathematical expressed as shown below.

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### 3.2.1 Triangular Membership Function

A triangular membership function is specified by three parameters *{a, b, c}* as

$$triangle(x;a,b,c) = \begin{cases} 0, & x<a \\ \frac{x-a}{b-a}, & a\le x\le b \\ \frac{c-x}{c-b}, & b\le x\le c \\ 0, & c\le x \end{cases}$$

(1)

The parameters *{a, b, c}* (with $a<b<c$) determine the $x$ coordinates of the three corners of the underlying triangular membership function.

### 3.2.2 Trapezoidal Membership Function

A trapezoidal membership function is specified by four parameters {a, b, c, d} as

$$trapezoid(x;a,b,c,d) = \begin{cases} 0, & x<a \\ \frac{x-a}{b-a}, & a\le x\le b \\ 1, & b\le x\le c \\ \frac{d-x}{d-c}, & c\le x\le d \\ 0, & d\le x \end{cases} \quad (2)$$

The parameters *{a, b, c, d}* (with $a<b<c<d$) determine the $x$ coordinates of the four corners of the underlying trapezoidal membership function.

### 3.2.3 Gaussian Membership Function

A Gaussian membership function is defined using 2 parameters {c,$\sigma$} where c represents membership functions centre and $\sigma$ represents the width of the membership function.

$$gaussian(x;c,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-0.5\left(\frac{x-c}{\sigma}\right)^2} \quad (3)$$

**Table 1: Values of parameters for inputs**

| Inputs | Membership function | *a* | *b* | *c* | *d* | *σ* |
|---|---|---|---|---|---|---|
| FOD | Very_Near | -2 | -1 | 1 | 2 | - |
| | Near | 1 | 2 | 3 | - | - |
| | Medium | - | - | 3 | - | 0.3 |
| | Far | 3 | 4 | 5 | - | - |
| | Very_Far | 4 | 5 | 7 | 8 | - |
| ROD | Very_Near | -2 | -1 | 1 | 2 | - |
| | Near | 1 | 2 | 3 | - | - |
| | Medium | - | - | 3 | - | 0.3 |
| | Far | 3 | 4 | 5 | - | - |
| | Very_Far | 4 | 5 | 7 | 8 | - |
| BOD | Very_Near | -2 | -1 | 1 | 2 | - |
| | Near | 1 | 2 | 3 | - | - |
| | Medium | - | - | 3 | - | 0.3 |
| | Far | 3 | 4 | 5 | - | - |
| | Very_Far | 4 | 5 | 7 | 8 | - |
| LOD | Very_Near | -2 | -1 | 1 | 2 | - |
| | Near | 1 | 2 | 3 | - | - |
| | Medium | - | - | 3 | - | 0.3 |
| | Far | 3 | 4 | 5 | - | - |
| | Very_Far | 4 | 5 | 7 | 8 | - |
| HA | N* | - | - | -160 | - | 25 |
| | N | - | - | -80 | - | 25 |
| | Z | - | - | 0 | - | 25 |
| | P | - | - | 80 | - | 25 |
| | P* | - | - | 160 | - | 25 |

**Table 2: Values of parameters for output**

| Inputs | Membership function | *a* | *b* | *c* | *d* | *σ* |
|---|---|---|---|---|---|---|
| HA | N* | - | - | -160 | - | 25 |
| | N | - | - | -80 | - | 25 |
| | Z | - | - | 0 | - | 25 |
| | P | - | - | 80 | - | 25 |
| | P* | - | - | 160 | - | 25 |

### 3.3 Fuzzy Rules

A number of rules are predefined forming a knowledge databse for the fuzzy logic controller. Few of the many predefined rules are shown below to create a better understanding of the rule definations.

**Rule 1: IF** (FOD is Very_Near) **AND** (ROD is Near) **AND** (BOD is Far) **AND** (LOD is Far) **AND** (HA is P) **THEN** (SA is N)

**Rule 2: IF** (FOD is Very_Near) **AND** (ROD is Far) **AND** (BOD is Far) **AND** (LOD is Very_Near) **AND** (HA is N) **THEN** (SA is P)

### 3.4 Mamdani Fuzzy Inference System

Fuzzy inference systems are categorized into three types i.e. Mamdani, Sugeno and Tsukamoto type. Out of these in this research Mamdani Fuzzy Inference System is adopted which is having five inputs along with a set of predefined rule database and it gives a crisp output. The steps that are followed in Mamdani Fuzzy Inference System are

1. Fuzzification
2. Rule Formation
3. Interference Engine or Fuzzy Reasoning
4. Deffuzification

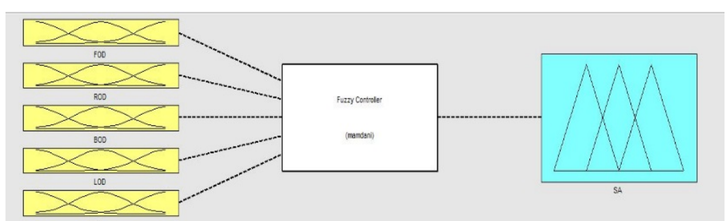


Fig. 7. Mamdani Fuzzy Inference along with inputs and output performed on Fuzzy Toolbox MATLAB R2013a

### 3.5 Defuzzification

A number of defuzzifications are available such as centroid of area method, mean-max method, first of maxima method, last of maxima method and weighted average method. Out of the-

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se, centroid of area method is adopted and is discussed below

### 3.5.1 Centroid of area method

$$SA = \frac{\int \mu_a(SA)\times SA\times d(SA)}{\int \mu_a(SA)\times d(SA)} \quad (4)$$

Where $\mu_a(SA)$ is the aggregated output of the membership functions and SA is the desired output i.e. steering angle. The above mentioned equation can be represented in a discrete form as,

$$SA = \frac{\sum_{i=1}^{n} \mu_a(SA_i)\times SA_i}{\sum_{i=1}^{n} \mu_a(SA_i)} \quad (5)$$

Where $\mu_a(SA_i)$ is defined as the sampled value of the aggregated output membership functions.

## 4 Analytical Description of the Experimental Robot

The POB-BOT is equipped with various distance measurement sensors such as infrared sensors and ultrasonic sensors. These additional sensors are added for navigational purpose. The wheels are powered by servo controlled motors and are helpful during navigation.

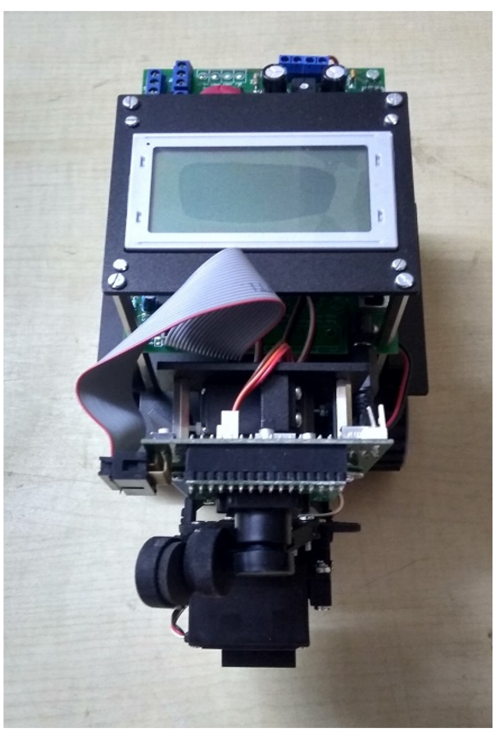

Fig. 8. POB-BOT (Mobile Robot)

## 5 Results (Experimental and Simulation)

### 5.1 Eperimental results

Figs. 9a-f show the motion of the mobile robot during experimental trial in a scenario i.e. a static fixed surrounding out of the ten trials performed.

Fig. 9a.

Fig. 9b.

Fig. 9c.

Fig. 9d.

Fig. 9e.

Fig. 9f

Fig. 9. Experimental view of robot during navigation

### 5.2 Simulation results

Results are verified in the simulation mode using MATLAB code derived out of the Fuzzy Inference System created in the MATLAB Fuzzy toolbox. The path followed by the mobile robot during real time trial followed the paths generated during simulations. One of such path in a cluttered environment is shown in Fig. 10.

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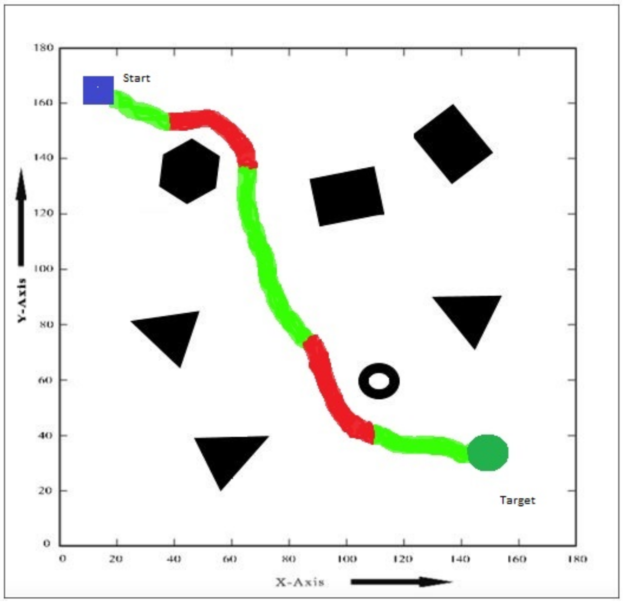


Fig. 10. Generated Path for the mobile robot

### 5.3 Tabulated result for path length covered by the robot to reach goal starting from the start position during experiment and simulation

**Table 3: Path length during simulation and experiment**

| No. of Exercise | Path Length in Simulation (PLS) from start to goal in millimeters | Path Length in Experiment (PLE) from start to goal in millimeters | Deviation $\frac{(\lvert PLS - PLE \rvert)}{PLS} \times 100$ | Average Deviation |
|---|---|---|---|---|
| 1 | 2292 | 2385 | 4.057 | 4.956 |
| 2 | 2182 | 2273 | 4.170 | |
| 3 | 2104 | 2230 | 5.988 | |
| 4 | 2228 | 2343 | 5.161 | |
| 5 | 2314 | 2416 | 4.407 | |
| 6 | 2525 | 2685 | 6.336 | |
| 7 | 2170 | 2288 | 5.437 | |
| 8 | 2364 | 2465 | 4.272 | |
| 9 | 2450 | 2558 | 4.408 | |
| 10 | 2288 | 2410 | 5.332 | |

Table 3 represents comparison of the path lengths obtained during the experimental trials with the simulation results for ten trials i.e. results obtained in ten different environments cluttered with obstacles. The tabulation shows the deviation of the experimental results from the simulated results and average deviation is calculated and is found to be within 6%.

### 5.4 Tabulated result for time taken by the robot to reach goal starting from the start position during experiment and simulation

**Table 4: Time taken during simulation and experiment**

| No. of Exercise | Time taken in simulation (TTS) from start to goal in milliseconds | Time taken in experiment (TTE) from start to goal in milliseconds | Deviation $\frac{(\lvert TTS - TTE \rvert)}{TTS} \times 100$ | Average Deviation |
|---|---|---|---|---|
| 1 | 4167 | 4390 | 5.351 | 5.378 |
| 2 | 3967 | 4200 | 5.873 | |
| 3 | 3825 | 4060 | 6.143 | |
| 4 | 4051 | 4250 | 4.912 | |
| 5 | 4207 | 4410 | 4.825 | |
| 6 | 4590 | 4810 | 4.793 | |
| 7 | 3945 | 4160 | 5.449 | |
| 8 | 4298 | 4560 | 6.095 | |
| 9 | 4454 | 4690 | 5.298 | |
| 10 | 4160 | 4370 | 5.048 | |

Table 4 represents comparison of the time taken during the experimental trials with the simulation results for earlier mentioned scenarios i.e. results obtained in ten different environments cluttered with obstacles. The tabulation shows the deviation of the experimental results from the simulated results and average deviation is calculated. The error is mainly due to slippage of robots between the wheels connected to actuators and ground. The percentage of error is found to be with in 6%.

## 6 CONCLUSION

This paper focuses on the research of fuzzy logic technique for effective navigation of wheeled mobile robot in a totally unknown scenario. There are several inputs and output from the developed fuzzy inference method. The five inputs are obstacle distances from the front, right, back and left and heading angle. The output is final angle calculated for steering of the robot. To validate the methodology developed comparisions have been made between simulation and experimental results and deviation is found to be within 6%. This technique can further be modified in the future by hybridizing for giving better navigational results.

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