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Navigation of Autonomous Firefighting Robots Using Fuzzy Logic Technique

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Abstract*— In this paper, a system design is presented for multiple autonomous firefighting robots that can navigate in a model house and extinguish the fire with a suppressant. The primary objective is to develop a navigation system for firefighting robots that can instantly reach the target area (fire zone) safely and extinguish the fire, thus preventing further damage to lives and property. Better navigation techniques are required for autonomous robots to reach the target in an unpredictable and dynamic environment. Recent studies suggest that fuzzy controllers manage well with the obscure information inherent to the subsystem interactions and non-linearity. In the proposed technique, the robot acts and reacts to situations using fuzzy logic control system. The input fuzzy members are turn angle between the robot head and the target, distance of the obstacles around the robot (front, left and right including other mobile robots), which are sensed by multiple ultrasonic sensors mounted on the robot. This paper presents results of velocity and obstacle avoidance analysis for firefighting robots navigating in a model house in different scenarios. The effectiveness and robustness of the proposed method is emulated by the simulation results presented which elucidates that the firefighting robots reach the target safely without hitting any obstacles. Thus, the proposed approach is suitable for navigation of firefighting robots in unknown environment to reach the fire accident zone in time without colliding with any obstacles.

Index Terms— **Firefighting, Fuzzy Logic, Mobile Robot, Obstacle avoidance.**

I. INTRODUCTION

Early discovery and concealment of flame can help in minimizing harm to life and property due to fire accident. As in many cases, human intercession is restricted owning to extreme natural conditions, including high temperature, extreme smoke, gas emissions and various hindrances that prevent restorative and salvage activities of humans. An effective intervention system can reduce the damage. Technology can play a major role in such interventions, with added safety. In recent times an autonomous firefighting robot, which can support or replace humans in monitoring and suppressing fire was developed. The robot is equipped with ultrasonic sensors for navigation, flame sensors for fire detection, a micro controller with an on-board computer, drive system, wireless communication modules and a fire extinguisher to suppress the fire. Different techniques were used by researchers for fire detection. As in [1] fire detection with a combination of ultrasonic and microwave Doppler sensor was developed. As in [2] adaptive fusion method to detect fire using a smoke sensor, temperature sensor and flame sensor was used. As in [3] an Intelligent Control and Sensor Fusion of a Mobile Robot Based Monitoring System in which the design, construction, and testing of a monitoring system based on a Khepera mobile robot was developed. The functions performed by the robot system are: (a) line following, (b) obstacle avoidance, (c) identification of test points along the path, and (d) recognition of the mark (bar code) located at each test point. In a similar manner, robots developed to compete in certain contests used line following technique for robot navigation [4]. The robots are programmed for a known environment that is not expected to change. But in real world applications the robots cannot reach the goal if they are ordered to perform in unfamiliar environments with dynamic obstacles. Due to these limitations we can apply fuzzy logic to solve the problem. Fuzzy logic is extensively applied in mobile robot navigation. Fuzzy logic controllers encompass different heuristics control mechanisms in different forms. For example, Else-If, If-Then and much more rules which help to build an efficient robot having different humanly like subjective and quantitative usefulness with control stream components. As in [5] the development of control technique for an autonomous mobile robot to navigate in a real world environment, which is capable of avoiding obstacles in its path was developed. It may be structured or unstructured, busy and an eccentrically changing environment. As in [6] rule based neuro fuzzy technique for multiple mobile robots which navigate in unknown environment was used. As in [7] a mobile robot which in case of fire accident will guide people reaching the safety area according to the programmed escaping path. In this paper, a navigation technique for the autonomous firefighting robots is developed to navigate the robot safely without colliding with both static and dynamic obstacles (Including other mobile robots) and to minimize the time taken by the robot to reach the fire accident zone. Once the robot receives the exact location (coordinates) of the fire accident area, the robot, using simple fuzzy rules, will directly reach the

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target area instead of searching for fire in every room, and thus saving precious time. In cases where fire occurs in multiple areas in a house or a building, a single robot will not be sufficient to handle it and the time it takes for the robot to suppress fire in the first place and reach the second may lead the fire to spread rapidly and cause damage to lives and property. Hence, we propose to use multiple robot system instead of single robot for fire detection and suppression. Multiple mobile robot system is more advantageous than one single robot system as they can finish tasks faster than a single robot.

Today multiple robots are used for transportation of material in industries, in hospital and for military applications. In many cases a centralized control system organizes the multiple robots to safely navigate or to keep formations. In [8] a centralized multi robot system was designed. Bluetooth technology for wireless data transfer between robots and the host computer was used, a multi-platform control library was implemented which provides access to sensors of individual robots and controls their movement.

II. MATERIALS AND METHODS

A. Robot Navigation

For any autonomous robot to navigate in an unknown and unpredictable environment with full of obstacles, goal seeking behavior, collision avoidance and obstacle avoidance behavior need to be designed. The navigation strategy includes global and local path planning. Information of obstacles and environment like a map is required for global path planning. In global path planning the environment is unknown, and sensors are used to detect the obstacles and avoid collision. Techniques like voroni diagram and potential field technique uses the information to plan a path to reach the target which is free of obstacles. However practically a precise and accurate data of obstacles in the environment as well sensory data is not available because of unpredictable obstacles appearing in the path of the robot and the need to alter the path to avoid collisions. Many navigation and multi robot obstacle avoidance techniques like vector field histogram method [9], potential field method, local adaptive navigation scheme and fuzzy logic technique were developed for the mobile robot to move safely in presence of obstacles. As in [10] software simulation of different navigation algorithm for mobile robots was presented which avoids obstacles in a static environment using both classical and fuzzy based algorithms and proved that the time taken by robot to reach the goal using a) Potential Field Method is 24950 milliseconds, b) Vector Field Histogram (plus) method is 5062 milliseconds, c) Local Navigation method is 40 milliseconds, d) Fuzzy navigation method is 31 milliseconds. According to the results provided in their paper, they have proved that the fuzzy logic is a more reliable and faster method to apply in relation to the other three methods. Using fuzzy logic, robots reach the target in the shortest possible time, requires fewer steps and is simple to implement in real time. The main reason behind using fuzzy logic technique is its simplicity and intuitive character which is essential for robot obstacle avoidance and collision avoidance with other mobile robots. So we have considered fuzzy logic technique system for firefighting robots to reach the target safely in less time.

Fuzzy logic is extensively applied in mobile robot navigation. In [11] a path planning navigation of mobile robot with obstacles avoidance (Including other robots) using fuzzy logic controller was developed. The proposed robot has 4 wheels, the front two being powered by stepper motors while the rear wheels are left free. On the robot we have installed ultrasonic sensors to obtain the distance from the obstacle and the target angle, and flame sensors designed to detect and respond to the presence of a flame or fire. The robot has an onboard controller in which the fuzzy controller is planted. The obstacle distance rules are activated along with the rules of the target base and it is defuzzified to obtain an output value. The output value is a position which is the optimum distance from the heat source and a safe distance away from the obstacles. Now the obstacle avoidance behavior takes its inputs from a set of ultrasonic sensors places in all directions around the mobile robot. Each sensor has distinct fuzzy sets which represent the position of the portable robot from the obstacle. The fuzzy sets are distinct because the forward facing sensor prioritizes and considers the forward obstacles to be greater hindrances than the side ones as they have a greater influence on the movement of the robot. As indicated by the information acquired by the sensors, the receptive mannerisms are decided by the fuzzy logic controller system based on the algorithm to maintain the velocity of the two driving wheels of the proposed mobile robot. The fuzzy logic control is shown in Fig 1. The proposed fuzzy system comprises of four components: fuzzification, fuzzy rule, fuzzy interface, and defuzzification. The inputs for the fuzzifier are the information gained by the sensors which then brings us to the fuzzy rules. The fuzzy rules are first compiled and appropriate path direction is set. It is then programmed into the

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controller. The rules which include the data from the ultrasonic sensors is defuzzified to produce an output value.

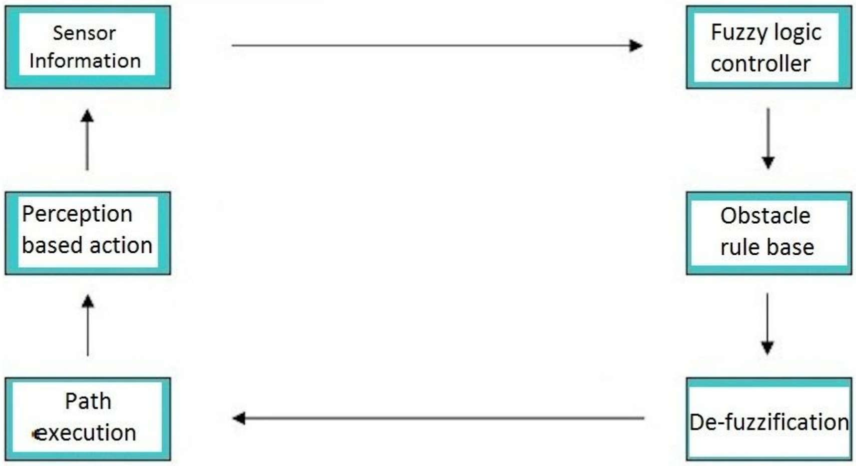

Fig 1. Fuzzy logic Control

B. Fire Fighting Technique

The paper mainly concentrates on navigation technique for autonomous firefighting robots that moves in a model house as shown in Fig 2. The objective of the robot is to reach the fire accident zone quickly and safely using fuzzy logic technique for navigation, obstacle avoidance and collision avoidance with other mobile robots. The time taken by robots to search the fire can be minimized or even eliminated if the fire is detected early by an automatic fire alarm system and the location of the fire is sent to the robot. Automatic fire alarm systems provide real-time surveillance, monitoring and automatic alarm in case of a fire. This early alarm can play an active part in reducing the fire damage. In [12] an automatic fire alarm system based on wireless sensor networks was designed. In a similar pattern, many detectors that periodically measure smoke concentration or temperature are deployed in every room of the building. These detectors report their monitoring information to a central computer via a self-organizing hierarchical wireless sensor network.

For the purpose of alarming the robot with the coordinates of the fire, localization is done using Dead – reckoning algorithm to estimate the actual configuration of the mobile robot and location coordinates of every room are defined with respect to pre-fixed, for example: (X7, Y7) for Room-7. This makes it easy for the robot to reach the location of the fire swiftly. As shown in Fig 2. we use two mobile robots placed at two different positions and coordinates of their positions with respect to the prefixed is also defined. (X01, Y01) for Robot-1, (X02, Y02) for Robot-2). In case of a fire accident in a room (for example Room-7), the fire alarm installed in the room detects it and will send information to the central computer and then the central computer will send the location of the room (Room-7) to the firefighting robots. Once target coordinates are given to the robots, they move towards the fire using fuzzy logic technique for goal seeking behavior for shortest path possible and moving safely around both static and dynamic obstacles including another mobile robot. The input functions are distance of the obstacles around the robot in all directions and turn angle between target and head of the robot and the output functions are left and right wheel velocity. By the time the robot reach the room where fire occurred, the fire may spread to another room and cause damage to both lives and property. To prevent his from happening the robot should react to any change in its environment and the specified target co-ordinates. So we have installed both UVtron flame sensor and IR sensor for fire detection. While the robot navigates in the building if it detects flame in its path, it will suppress the flame by engaging the pump and suppressant. As we are using multiple robots for fire suppression and if fire spreads from one room to another room the fire alarm in the room will be activated and the centralized computer sends the new room co-ordinates to the remaining robots so that the situation can be brought under control.

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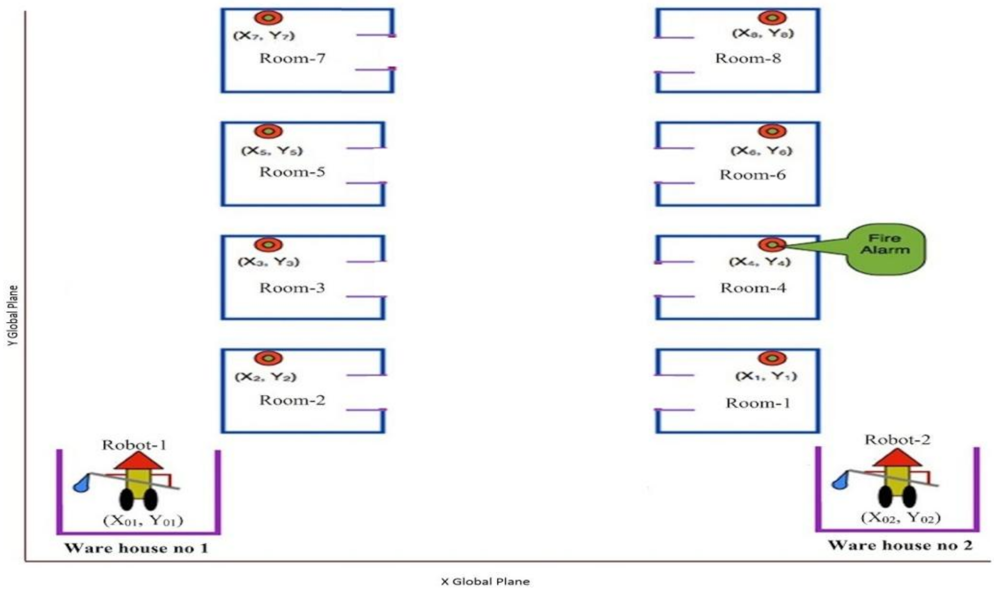

Fig 2. Model House in Which Autonomous Firefighting Robot Moves

III. RESULTS

A. Robot Localization

Localization is the basic method of navigation which includes sensing, mapping, localization, planning and control. Attaining the robot's position with respect to the reference frame will enable us to navigate the mobile robot in an unmodified environment. The reference frame is Cartesian. Using Dead reckoning systems we can estimate the current position of the mobile robot with respect to an initial point by measuring linear and angular velocities or accelerations. The robot position can be estimated by keeping track of the extent to which the wheels of the robot turn. Incremental encoders are attached to a rotating shaft which maintains the count as the wheel turn Quadrature signals are generated by these encoders which aids the robot to determine both velocity and direction of the wheels. In global coordinate system, the initial position of the robot is given by the triple (X, Y, θ) as shown in the Fig 3. If the robot turns by an angle and moves a certain distance denoted by Δθ and ΔS respectively, the new position of the robot denoted by ($X^{|}$, $Y^{|}$, $\theta^{|}$) can be calculated readily. This method aids the centralized computer to locate the robot at any instant and navigate it towards its target co-ordinates. The disadvantage of this localization method is that while calculating the new position of the robot from its previously occupied positions, there are a number of error sources of differential encoders springing up due to environments factors such as uncertainty of wheel diameter, wheel slippage, misalignment of the wheels. However a recent study has shown that these errors can be made negligible by using sensory fusion process with variety of sensors like gyroscope, compass, ultrasonic sensor etc. [13], [14]

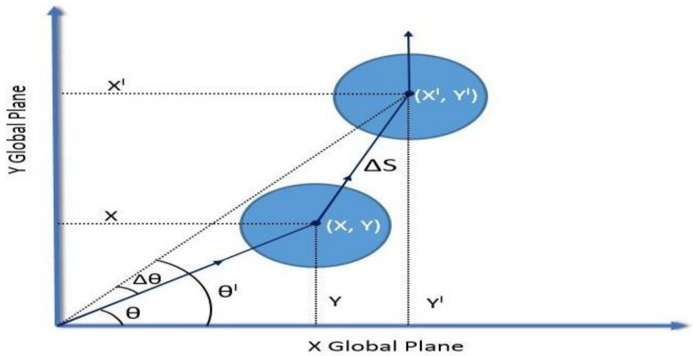

Fig 3. Robot Position in Global Reference Frame

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B. Fuzzy rules for goal reaching, obstacle avoidance and collision avoidance behavior

The goal reaching behavior tends to drive the robot from a given initial position to a target position. This behavior drives the robot to the left to the right or forward depending on the information received by different sensors on the robot and incremental position of the robot in global plane through series of encoders. Fuzzy rules from 28 to 33 are for target finding shown in Table 1. The input signals to fuzzy navigation algorithm are the distances between the robot and obstacles to the left, front, and right locations as well as the heading angle between the robot and a specified target. When the target is located to the left side of the mobile robot, a heading angle (head-ang) is defined as negative; when the target is located to the right side of the mobile robot, a heading angle (head-ang) is defined as positive. According to acquired range information by sensors, the fuzzy logic algorithm is used to control the velocities of the two driving wheels of robot. When the robot is in proximity with the obstacle or any other robot and is about to collide, it changes its path, speed and heading angle in order to reach the destination. This is why obstacle avoidance is important and it assures a collision free, target seeking behavior. The fuzzy rules that are incorporated while the robot avoids the obstacle is given in a tabular form below. When the robot is close to both static and dynamic (Including Other Mobile robots) obstacles, it should slow down and adjust its steering angle and the mentioned principle is used for every type of curvilinear path. Fuzzy rules from 1 to 27 are for obstacle avoidance including mobile robot and wall following. An example of a command in Table 1. is mentioned below for better understanding. *Rule 1:* If left obstacle distance (Left_obs) is near and right obstacle distance (Right_obs) is near and front obstacle distance (Front_obs) is near and heading angle (Head_ang) is any then left wheel velocity (Left_vel) is slow and right wheel velocity (Right-vel) is fast. The robot then takes left turn accordingly. *Rule 2:* If left obstacle distance (Left_obs) is near and right obstacle distance (Right_obs) is near and front obstacle distance (Front_obs) is medium (Med) and heading angle (Head_ang) is any then left wheel velocity (Left_vel) is slow and right wheel velocity (Right-vel) is slow. The robot's motion will slow down accordingly.

TABLE 1: Rules – Fuzzy Logic System for Target Seeking and Obstacle Avoidance

Rule no	Operator	Left_obs	Operator	Right_obs	Operator	Front_Obs	Operator	Head_ang	Operator	Left_vel	Right_vel
1	If	Near	And	Near	And	Near	And	Any	Then	Slow	Fast
2	If	Near	And	Near	And	Med	And	Any	Then	Slow	Slow
3	If	Near	And	Near	And	Far	And	Any	Then	Med	Med
4	If	Near	And	Med	And	Near	And	Any	Then	Med	Slow
5	If	Near	And	Med	And	Med	And	Any	Then	Med	Slow
6	If	Near	And	Med	And	Far	And	Any	Then	Fast	Med
7	If	Near	And	Far	And	Near	And	Any	Then	Fast	Slow
8	If	Near	And	Far	And	Med	And	Any	Then	Med	Slow
9	If	Near	And	Far	And	Far	And	Any	Then	Fast	Med
10	If	Med	And	Med	And	Near	And	Any	Then	Fast	Slow
11	If	Med	And	Med	And	Med	And	Any	Then	Slow	Slow
12	If	Med	And	Med	And	far	And	Any	Then	Fast	Fast
13	If	Med	And	Near	And	Near	And	Any	Then	Slow	Fast
14	If	Med	And	Near	And	Med	And	Any	Then	Slow	Med
15	If	Med	And	Near	And	Far	And	Any	Then	Slow	Med
16	If	Med	And	Far	And	Near	And	Any	Then	Med	Slow
17	If	Med	And	Far	And	Med	And	Any	Then	Med	Fast
18	If	Med	And	Far	And	Far	And	Any	Then	Fast	Med
19	If	Far	And	Near	And	Near	And	Any	Then	Slow	Med
20	If	Far	And	Near	And	Med	And	Any	Then	Med	Fast
21	If	Far	And	Near	And	Far	And	Any	Then	Med	Fast
22	If	Far	And	Med	And	Near	And	Any	Then	Slow	Fast
23	If	Far	And	Med	And	Med	And	Any	Then	Slow	Med
24	If	Far	And	Med	And	Far	And	Any	Then	Med	Fast
25	If	Far	And	Far	And	Near	And	Any	Then	Fast	Slow
26	If	Far	And	Far	And	Med	And	Any	Then	Fast	Med
27	If	Far	And	Far	And	Far	And	Any	Then	Fast	Fast

28	If	Far	And	Far	And	Far	And	P	Then	Fast	Med
29	If	Far	And	Far	And	Med	And	N	Then	Med	Fast
30	If	Far	And	Far	And	Far	And	Z	Then	Fast	Fast
31	If	Far	And	Far	And	Med	And	P	Then	Slow	Med
32	If	Far	And	Med	And	Far	And	N	Then	Med	Fast
33	If	Med	And	Far	And	Far	And	Z	Then	Fast	Fast

When the acquired information from the sensors shows that there are no obstacles around robot, the main reactive behavior of the robot is goal reaching behavior. Intelligent controller mainly adjusts robots motion direction and quickly moves it towards the target if there are no obstacles around the robot. Velocity analysis and obstacle avoidance is done using MATLAB. Each member function is assigned for unique control parameters. The parameters taken into consideration are distance of obstacle from the robot to its left, right, and front. For example, if the obstacle is at a distance ranging from 0 to 0.6 it is assigned as near, 0.6 to 0.9 is assigned as medium and 0.9 to 1.0 is assigned as far. The same is applicable to “Right_obs”,”Front_obs” and “Frontobs”. Similarly the “heading angle” membership function is defined. Different input fuzzy and output fuzzy set is shown with their member functions in Fig 4.

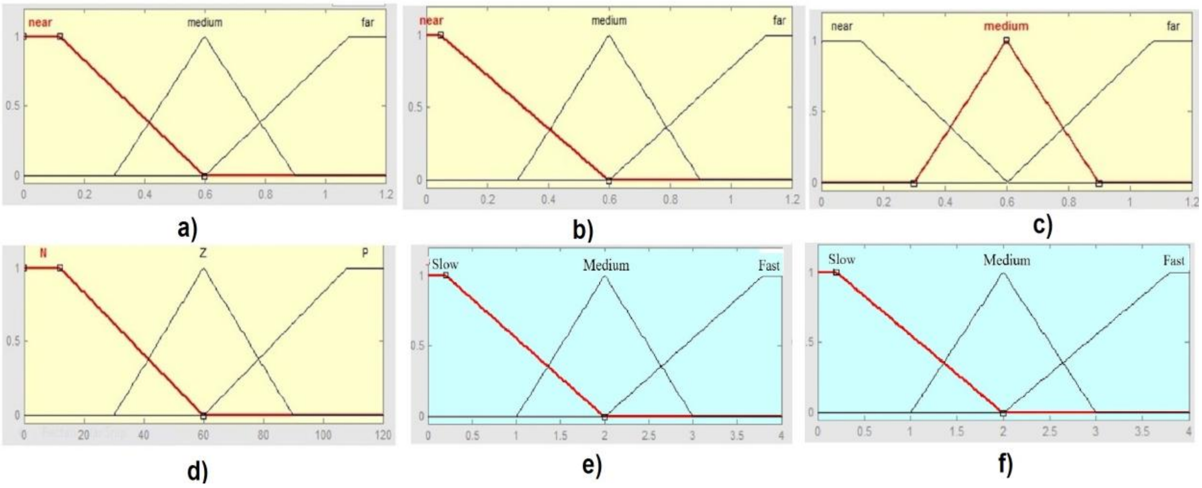

Fig 4. Input Member Functions a) Left Obstacle Distance b) Right Obstacle Distance c) Front Obstacle Distance d) Heading Angle; Output member functions e) Right Wheel Velocity f) Left Wheel Velocity

C. Velocity Analysis

An analysis was done to confirm if the left wheel velocity and right wheel velocity diverts or if it actually does follow the rule base. The data is presented in Table 2. which validates that the velocity change of the left and right wheel is in accordance with our requirements. As the obstacle comes in proximity to the robot (front, left, right), the velocity of the right and left wheel will vary according to the distance of the former mentioned input parameter. The schematic diagram of fuzzy logic is shown in Fig 5.An example in the Fig 5.is mentioned below.

Input: Front obstacle distance is 0.61 m, Right obstacle distance is 1.01 m, Left obstacle distance is 0.101 m, Heading angle is 94.8 degree.

Output: Left wheel velocity is 2.03 m/sec; Right wheel velocity is 0.714 m/sec

TABLE 2: Velocity Analysis of Firefighting Robot

Left Obstacle (mt)	Right obstacle (mt)	Front Obstacle (mt)	Heading Angle (degree)	Left wheel velocity (m/sec)	Right wheel velocity (m/sec)
0.12	0.84	0.418	Any	2.55	0.826
0.302	0.715	0.418	Any	2.42	0.876
0.456	0.715	0.418	Any	1.92	3.74
0.926	0.715	0.418	Any	2	2
0.13	0.293	0.187	Any	0.74	3.26

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0.13	0.466	0.187	Any	1.58	1.64
0.13	0.907	0.187	Any	3.26	0.74

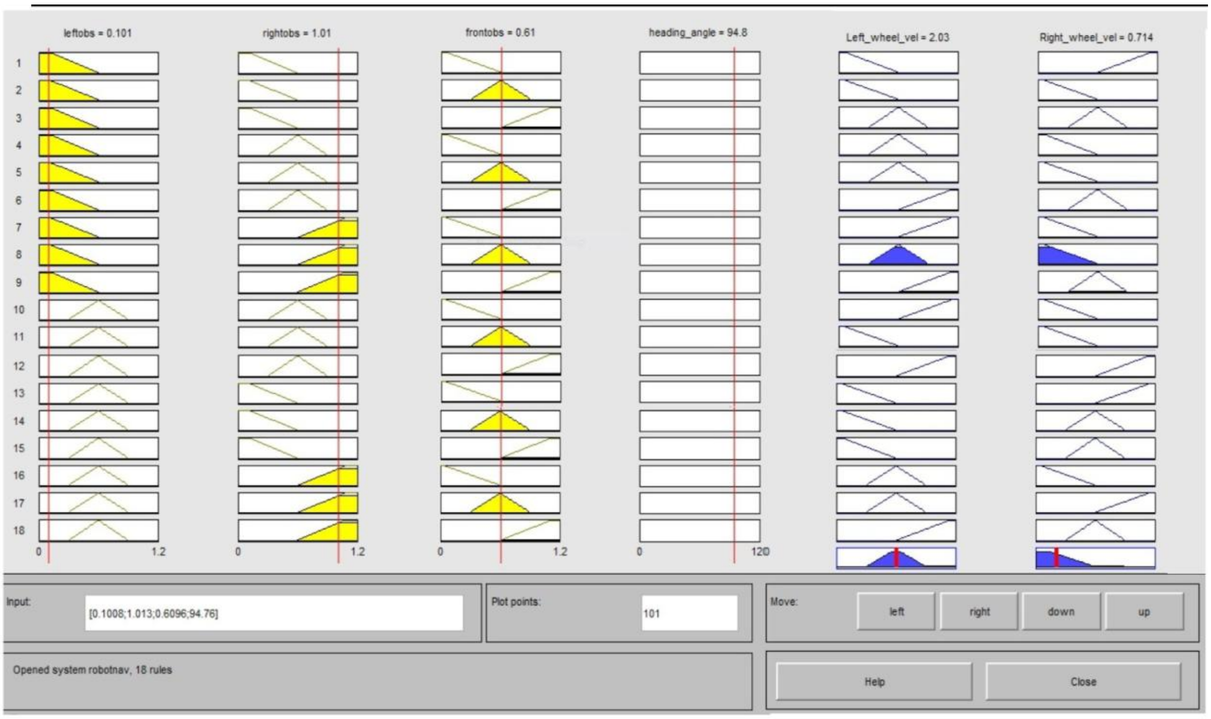

Fig 5. Schematic diagram of fuzzy logic for navigation of robots

D. Obstacle avoidance analysis

In this analysis segment, different cases are considered

1. Single robot single target (When there is a fire in one Room), 2. Double robot double target (When there are fires in two rooms at same time), 3. Double robot single target (Additional support given by robot-2 to robot-1). For all these cases we have validated, the robot reaches the destination safely without collision.

1. Single robot single target: This is the case in which there is fire in one room and the target coordinates are sent to a single robot as (100,100) .The robot is initially at (0, 0) in warehouse no-1. Three obstacles are placed at (40, 40), (60, 60), and (80, 80) respectively. As shown in Fig 6. the robot reached the target safely avoiding obstacles. Here target refers to the co-ordinates of room where fire occurred received by the robot from main controller. After reaching the target zone the robot starts to suppress the fire.

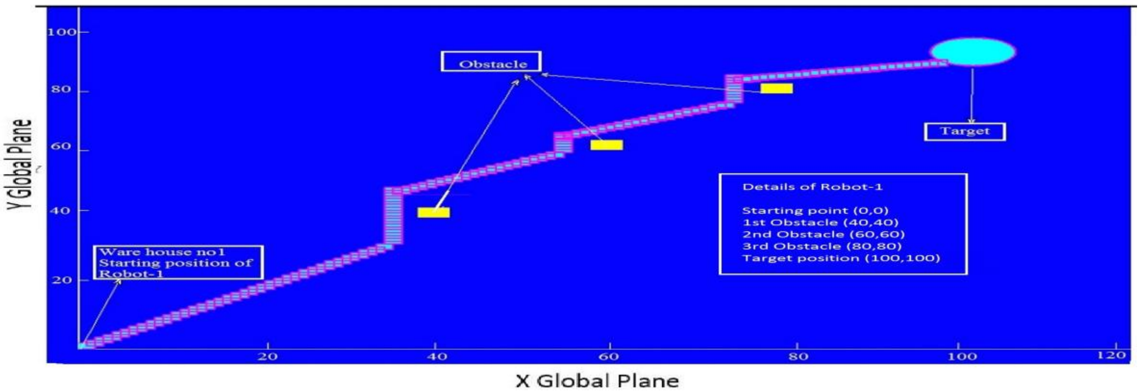

Fig 6. Obstacle avoidance for single robot and single destination

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2. Double robot, double destination: This is the case in which there is fire in two rooms at the same time. Different target coordinates are given to two robots that were initially at different locations. Robot-1 is initially at (0, 0) warehouse no-1 and the target coordinates given to robot-1 is (60, 60). Three different obstacles are placed at (30, 30), (40, 40), and (50, 50) respectively. As shown in the Fig 7.robot-1 reached the target safely by avoiding obstacles (Target here refers to room-1 coordinates where the fire is detected). On reaching the target zone, the robot starts to suppress the fire. Robot-2 is initially at (200, 0) warehouse no-2 and target coordinate given to robot-2 is (100, 100). Three different obstacles are placed at (180, 20), (160, 40), and (140, 60) respectively. As shown in the Fig 7. robot-2 reaches the target safely. (Target here refers to room-2 coordinates where fire is detected). On reaching the target zone, the robot starts to suppress the fire.

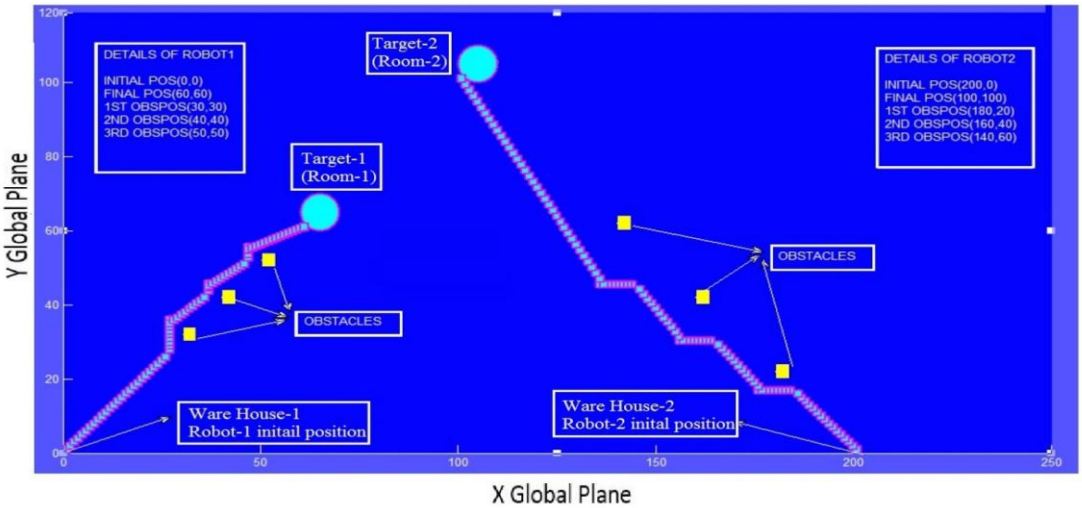

Fig 7. Obstacle avoidance for double robot and double destination

3. Double robot, single destination: This is the case in which there is fire in a room and the robot-1 needs additional support of robot-2 (a case where the suppressant is limited and extra quantity is needed). Initially robot-1 is at warehouse-1 (0, 0) & robot-2 is at ware house-2 (200, 0). Target coordinates for the both robot-1 & robot-2 is same (100, 100). For robot-1 three different obstacles are placed at (40, 40), (60, 60), and (80, 80) respectively. For robot-2, obstacles are placed at (180, 20), (160, 40), and (140, 60) respectively. As shown in the Fig 8.both the robots reached the target safely. (Target here refers to room-1coordinates where fire is detected). On reaching the target zone the robots starts to suppress the fire.

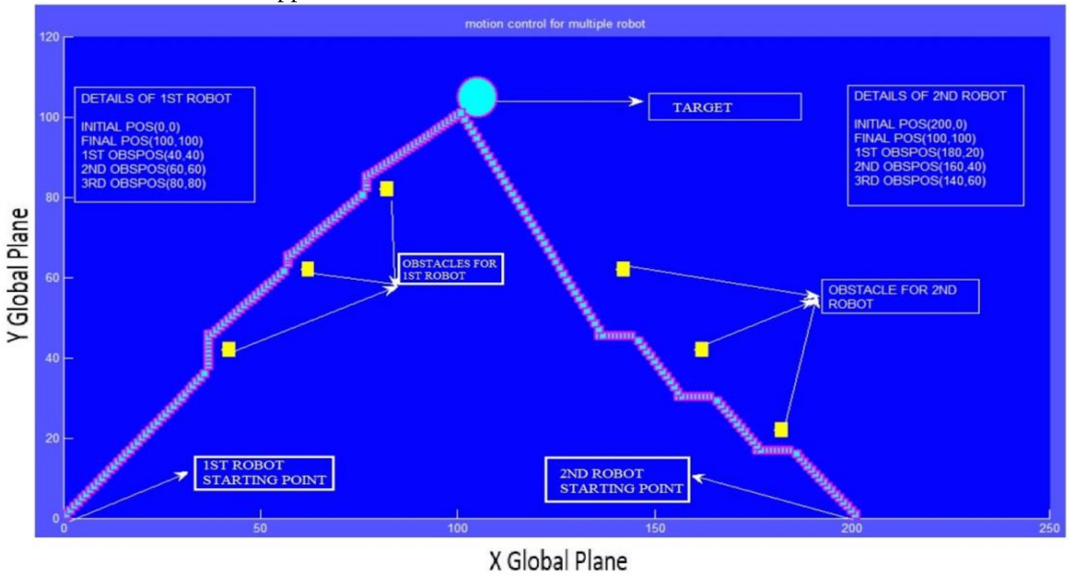

Fig 8. Obstacle avoidance for double robot and single destination

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IV. CONCLUSION

The paper discussed Fuzzy logic control technique for navigation and obstacle avoidance for multiple autonomous fire-fighting robots that can search and extinguish fire. In an earlier model the robot searches for the flame in every room and eventually reaches the fire accident zone, but by that time the fire may have spread rapidly and caused damage to both property and lives. Therefore, we proposed a fire detecting model in which we provide the location of the fire accident zone to the robot through centralized computer, using fire sensors in different places so that the robot will reach the fire accident zone in time and can save lives. Compared to earlier similar work in which line following techniques were used for firefighting robot navigation in a known and unchanging environment (not feasible in real world environment) we used fuzzy logic control for reaching the fire zone by navigation in an unpredicted environment by avoiding obstacles and avoiding collision with other mobile robots. The development of simple set of control rules for goal reaching and obstacle avoidance of robots is explained. An analysis was done to confirm if the left wheel velocity and right wheel velocity diverts or if it actually does follow the rule base. Data is presented to validate the velocity change of the left and right wheel is in accordance with our requirements.

Using MATLAB, we have shown that the Simulation results on mobile robot navigation in various environments and cases like Single robot single target (When there is fire in one room), double robot double target (When there is fire in two rooms), double robot single target (When the robot-1 needs additional support) are done and the results show that the proposed navigation technique is suitable for firefighting robots to navigate safely without collision with obstacles. To make the firefighting robot more efficient while searching fire, some enhancements are need to be done in future work by installing infrared sensors which can detect fire from long range so that fire can be sensed earlier. Our future work also includes developing a shortest path which is displayed in the robots screen to guide the people to the safest position in less time during fire accident.

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