Path Tracking Control of a Mobile Robot using Fuzzy Logic

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Abstract **- Recently, the study and development of the mobile robot is considered as a very important issue for many researchers. This is because the wide range of mobile robot applications in real life. One of the most important mobile robot tasks is the control of its navigation in tracking its predefined path. This also need a good capability in avoiding any static or dynamic obstacles that the mobile robot face in its route until reaching its destination. The difficulty in finding a good mathematical model for tShe mobile robot used in this research "Robotino® from Festo company" made the decision to use fuzzy logic to design a controller capable to introduce a safe Robotino® navigation. Fuzzy logic controller needs information about Robotino® features and behavior in order to build its rule base which are inspired from human experience in such application. These rules can be easily programmed to bring out an efficient controller. Sugeno algorithm is implemented which the experiments results validated its efficiency. Fuzzy logic controller with 153-fuzzy rule is used for controlling the Robotino® path tracking issue, while another fuzzy logic controller with 27-fuzzy rule is applied for the Robotino® obstacle avoidance feature. Matlab is used as a tool to implement the two proposed fuzzy controllers. Many real-time experiments have been conducted in the Faculty of Engineering research laboratory at Philadelphia University. Results reflect the good abilities of the proposed controllers.**

Index Terms - Mobile Robot, Robotino®, Path Tracking, Obstacle Avoidance, Fuzzy Logic Controller.

I. INTRODUCTION

Nowadays, the vast development in mobile robots led to a wide variety of industrial, agricultural and military applications. Since the mobile robot can move in all directions, thus controlling its path is one of the most important issues to make it move in a safe way, i.e. it can avoid any obstacle that may be faced in its predefined path without any human intervention. This cannot be achieved easily using classical control approaches. Thus fuzzy logic control was designed to fulfill such a goal based on feeding human experience.

The performance of fuzzy logic controller was illustrated using a simulation study by [1]. Here fuzzy logic controller of nine IF-THEN rules was implemented with mobile robot torques and velocities taken as controller inputs. Robot position and orientation were controlled using Mamdani fuzzy algorithm. A comprehensive simulation study was used to reflect the good controller capabilities. Fuzzy logic controller had been presented by [2] to control a trajectory tracking for a wheeled mobile robot. The controller was fed by the errors in postures of mobile robot. Based on these input signals the fuzzy controller generated action signals to move robot motors to left and right directions. Both simulation and real experiments were evaluated to demonstrate the effectiveness of the proposed algorithm which proved the good tracking and robustness obtained abilities.

Mobile robot tracking to straight and curved paths had been evaluated using fuzzy logic controller by [3]. Steering angle and robot velocity were considered as a controlled variables. A camera was used to capture images for the path ahead then the vision system determines the error and the required curvature path. An experiment had been applied to test the effectiveness of the proposed fuzzy velocity controller with an encouraging results. The major problem of forcing the mobile robot to track a path planned on a map was faced by [4]. A path tracking method which was based on fuzzy logic, PI and P controllers for four wheeled autonomous mobile robots was tested through simulation study. Many performance indices were taken as the length of the route and tracking duration to measure the proposed control algorithm capabilities.

A nonlinear controller for an omnidirectional mobile robot was presented by [5]. The controller had two loops the outer and the inner ones. Trajectory Linearization Control (TLC) was implemented to design both controller loops. A combination of the onboard sensor and the vision system data was achieved using a sensor fusion method. This provided accurate and reliable robot position and orientation measurements. To obtain a full control of saturation avoidance, a time-varying filter to reshape an abrupt command trajectory was applied. Results of hardware-in-the-loop (HIL) as real-time implementation had reflected the accurate trajectory tracking of a large class of 3-degrees-of-freedom (3DOF). PI-fuzzy path planner was suggested and designed by [6], along with velocity and acceleration filtering was implemented as well, these were introduced to improve the discrete-time linear quadratic tracking approach with appropriate speed monitoring algorithm. A comparative study had been evaluated with PID-controller. Results reflected and confirmed the modelling and the experimental results.

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Multi-input fuzzy rules emulated networks (MIFRENs) adaptive controller was introduced by [7] to control mobile robot systems in the discrete-time domain. The main issue was to guarantee close-loop performance and system robustness for all parameters inside (MIFRENs). A superior performance had been compared to that of an algorithm that uses only an embedded controller. A better technique was developed in navigating mobile robot in a real environment by [8]. The action and reaction of the robot was addressed by fuzzy logic control system. The input fuzzy members were used to turn angle between the robot head and the target. Distance of the obstacles was presented to cover all around the robot (left, right, front and back). While measurements had been done using series of infrared sensors. The presented fuzzy logic controller for navigation of robot had been applied in all complex and adverse environment. The obtained results were good for the tested conditions.

As a conclusion, every application has its own limitations and one should choose the control algorithm which will approximately match the requirements. Therefore any work should be started with a design strategy after pointing out the needed requirements and performance to choose the best control algorithm that will help in reaching the desired goal. The underlying research aims at designing fuzzy controllers that would help the Robotino® to reach its target in a safe way. This needs a prior knowledge about the Robotino® features and capabilities to accomplish an acceptable controller design.

II. SYSTEM DISCRETION

Robotino® as shown in Fig.1 is a mobile robot system with an Omni-directional drive, a learning system for basic and further training, and a research and development platform for universities and colleges [9]. The Robotino® is an automatic numerous device with sensors, a camera and a high-performance controller provide the system with the required “intelligence”. When correctly programmed, it can freely perform the tasks required from it, or can perform as a research and development platform for artificial intelligent systems. It is mainly composed of:

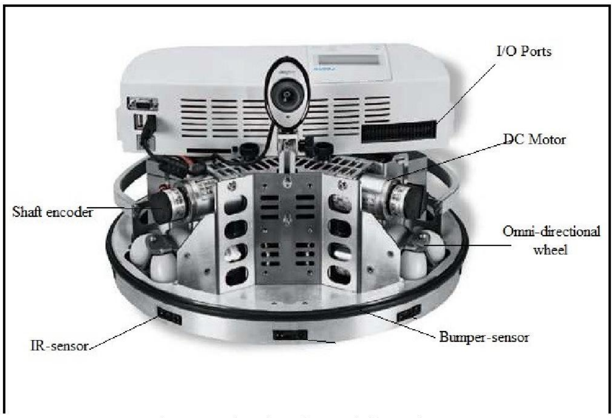


Fig.1 Robotino® mobile robot

A. The Drive Units

Robotino® is driven by three independent, omnidirectional drive units shown in Fig.2. They are mounted at an angle of 120° to each other. Each of the three drive units consists of the following components:

- DC Motor,
- Shaft encoder,
- Omni-directional wheel,
- Gear unit; and
- Toothed belt.

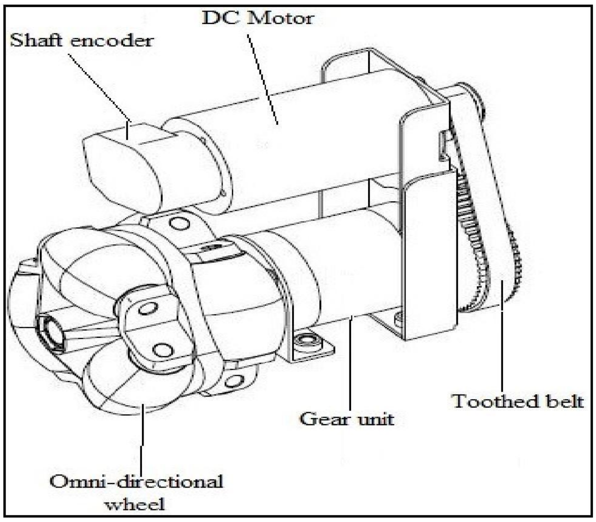


Fig.2 Robotino® driving unit

B. Infrared (IR) Distance Sensors

Robotino® is equipped with nine infrared distance measuring sensors which are mounted in the chassis at an angle of 40° to one another as shown in Fig.3.

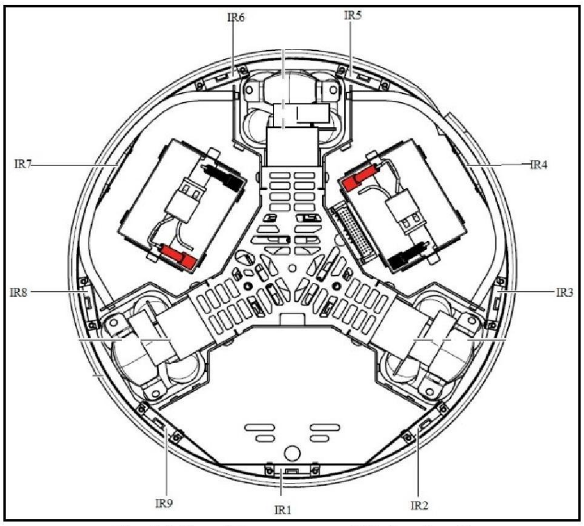


Fig.3 Nine IR sensors of Robotino®

These sensors are capable of accurate or relative distance measurements to objects at distances of (4 to 30 cm) which are equivalent to (0.4 to 2.5 volt) [9].

C. Odometry

The word odometry is composed from the Greek words ode (route) and metron (measure) [10]. Thus odometry means the use of data from motion sensors to estimate change in position over time. Odometry is used by some robots, whether they be legged or wheeled, to estimate (not determine) their position relative to a starting location. This method is sensitive to errors due to the integration of velocity measurements over time to give position estimates.

III. FUZZY LOGIC CONTROLLERS DESIGN

Getting a comprehensive knowledge about the Robotino® system dynamic along with its ability to accept a programmed high level control algorithm, a complete fuzzy logic controllers are designed to move Robotino® in a safe way to track its predefined path.

A. Path tracking Fuzzy controller

Refer to system block diagram Fig.4, the following steps will show the whole controller design.

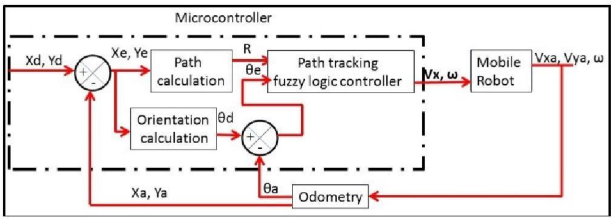


Fig.4 System block diagram: Path tracking fuzzy control

Where:

- Xd, Yd, θd are the desired values of X, Y position and orientation respectively.
- The actual values of the positions (Xa, Ya) and orientation (θa) are measured using the odometry as a feedback transducer, based on the actual linear velocities and the actual angular velocity (Vxa, Vya, and ωa) respectively.
- Comparator is used to calculate the error for each variable and the desired orientation as below:
  Xe = Xd – Xa, Ye= Yd – Ya, θe = θd – θa (1)
  θd= atan2 (Ye/ Xe) (2)
  Where atan2 is a built in function that recalls the angle based on its right quarter.
- The required path Resultant distance (R) is calculated as:

$$R= \sqrt{(\text{Xd}-\text{Xa})^2 + (\text{Yd}-\text{Ya})^2} \quad (3)$$

- The resultant instant distance (R) along with the orientation error (θe) will be fed as the input variables to the proposed Fuzzy Logic controller.

By definition, the fuzzy logic controller has three main processing parts:

1. Fuzzification Process

After many trials to get the best fuzzy sets for (R) and θe based on their possible variation, two fuzzifiers are obtained. R-fuzzifier is set to have nine symmetric fuzzy sets spread over a universe of discourse of (0–7 meters) as shown in Fig.5.

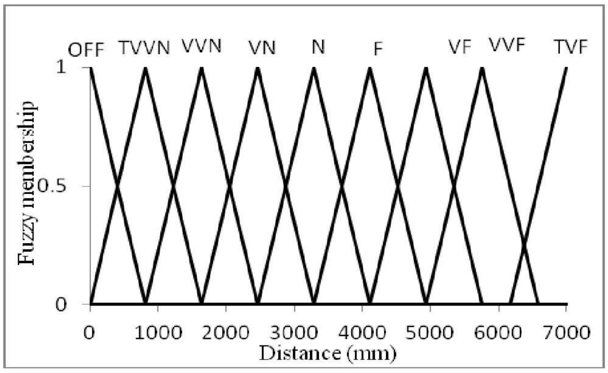


Fig.5 Resultant (R) fuzzy sets

Where the nine fuzzy sets are named with indicative linguistic named as :

OFF (O), Too Very Near (TVN), Very Very Near (VVN), Very Near (VN), Near (N), Far (F), Very Far (VF), Very Very Far (VVF), Too Very Far (TVF).

While as for θe, its universe of discourse varies from -180° to 180° with non-symmetric fuzzy sets as shown in Fig.6. They have been extracted after many trails to get the best system response, with their linguistic abbreviation meanings are defined as below:

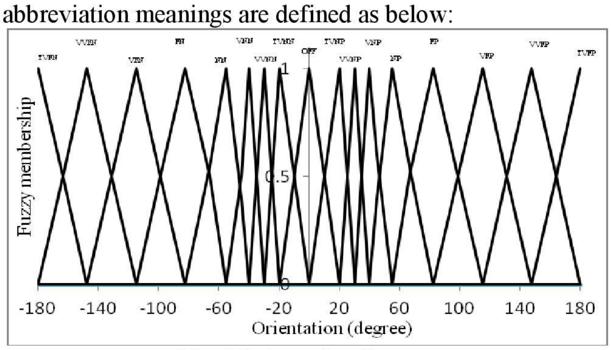


Fig.6 Orientation fuzzy sets

Too Very Far Negative (TVFN), Very Very Far Negative (VVFN), Very Far Negative (VFN), Far Negative (FN), Near Negative (NN), Very Near Negative (VNN), Very Very Near Negative (VVNN), Too Very Near Negative (TVNN), OFF (O).
Too Very Near Positive (TVNP), Very Very Near Positive (VVNP), Very Near Positive (VNP), Near Positive (NP), Far Positive (FP), Very Far Positive (VFP), Very Very Far Positive (VVFP), Too Very Far Positive (TVFP).

2. Fuzzy Production Rules

As for the underlying system, fuzzy production rule will take the form of:

IF R is F AND θe is FN THEN Vx is OFF, W is N

That is:

If resultant R is far and θ error is far negative then the linear velocity in x-axis is OFF, and the angular velocity is negative.

So based on fuzzification process of input variables, 153-fuzzy production rules are extracted as listed in Table 1.

Table 1 System fuzzy production rules

R / θe	OFF		TVVN		VVN		VN		N		F		VF		VVF		TVF	
	VX	ω	VX	ω	VX	ω	VX	ω	VX	ω	VX	ω	VX	ω	VX	ω	VX	ω
TVFN	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N
VVFN	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N
VFN	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N
FN	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N
NN	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N
VNN	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N	O	N
VVNN	O	SN	O	SN	O	SN	O	SN	O	SN	O	SN	O	SN	O	SN	O	SN
TVNN	O	SN	O	SN	O	SN	O	SN	O	SN	S	SN	O	SN	O	SN	O	SN
OFF	O	O	SL	O	F	O	F	O	F	O	F	O	F	O	F	O	F	O
TVNP	O	SP	O	SP	O	SP	O	SP	O	SP	O	SP	O	SP	O	SP	O	SP
VVNP	O	SP	O	SP	O	SP	O	SP	O	SP	O	SP	O	SP	O	SP	O	SP
VNP	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P
NP	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P
FP	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P
VFP	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P
VVFP	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P
TVFP	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P	O	P

3. Defuzzification Process

The output crisp action value is calculated using Sugeno action. Thus for linear velocity Vx, three sets of action "OFF (O), Slow (SL), Fast (F)" which are related to speed of (0 mm/s, 200 mm/s, 300 mm/s) respectively are shown in Fig.7. They have been chosen to ensure that when any obstacle is detected there will be enough time to take an action preventing any possible collision.

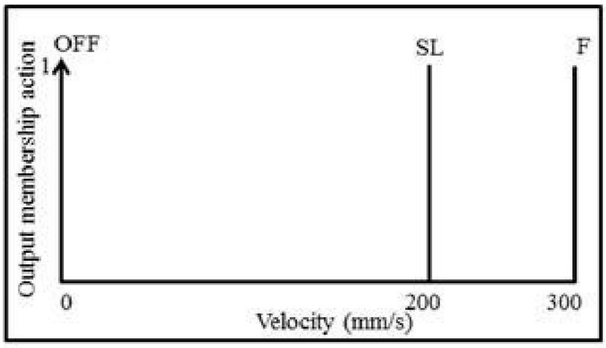


Fig.7 Sugeno fuzzy action for (Vx)

Fuzzy action concerns the angular velocity (ω) is described in Fig.8 Which shows the different actions Negative (N), Small Negative (SN), OFF (O), Small Positive (SP), Positive (P) along with their Sugeno action crisp value of -18 rpm, -8 rpm, 0 rpm, 8 rpm, 18 rpm respectively. The universe of discourse is chosen to keep Robotino® rotation toward the required orientation with non-oscillatory manner.

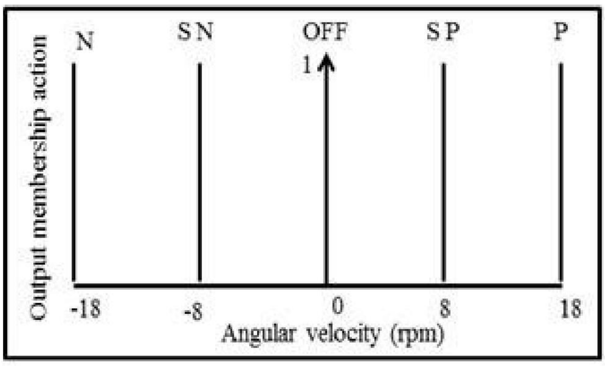


Fig.8 fuzzy action for angular velocity (ω)

B. Obstacle Avoidance Fuzzy Controller

It is of high importance to include the property of obstacle avoidance to the proposed fuzzy logic controller. This feature helps the mobile robot to track its predefined path safely. Making use of the three infrared sensors measurements (left, front and right). Which are IR2, IR1 and IR9 shown in Fig.3 respectively, with the rang of (4 - 40 cm) which corresponds to (0.4 - 2.5 volt). The front one is placed at the center of Robotino® which is 40° far from left and right ones. If it happens that obstacle exists at the center, the priority to move right is recommended.

1. Fuzzification Process

A fuzzy logic control for avoiding static obstacle is added. This controller receives three input analog inferred sensor signals representing obstacle distance. They are fuzzified into three fuzzy sets each as in Fig.9 below.

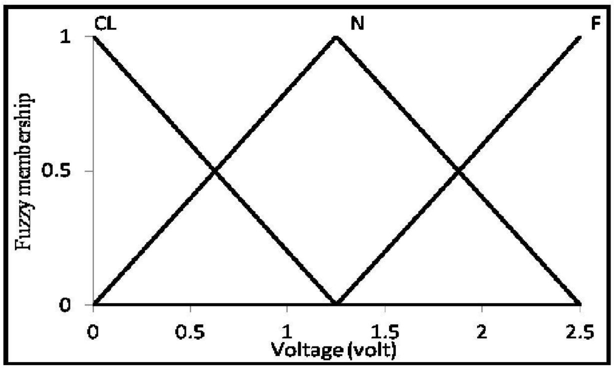


Fig.9 IR measured voltage fuzzification process

Where: CL, N, F stand for Close, Near and Far distance respectively

2. Fuzzy Production Rules

Twenty five fuzzy production rules as in Table 2 have been extracted with their Sugeno action related to movement in Y-direction. The two shaded fuzzy rules are skipped because they conflict with the design algorithm in case of two close obstacles states may occur.

Table 2 Obstacle avoidance fuzzy rules

Rule NO.	Situation	IR9	Operation	IR1	Operation	IR2	Consequent	Then
1	IF	0	And	1	And	0	Then	Right
2	IF	0	And	0	And	0	Then	Right
3	IF	0	And	1	And	0	Then	Right
4	IF	0	And	0	And	0	Then	Right
5	IF	0	And	0	And	0	Then	Right
6	IF	0	And	0	And	1	Then	Right
7	IF	0	And	0	And	1	Then	Right
8	IF	0	And	0	And	0	Then	Right
9	IF	0	And	0	And	0	Then	Right
10	IF	0	And	0	And	0	Then	Left
11	IF	0	And	0	And	1	Then	Right
12	IF	0	And	0	And	0	Then	Right
13	IF	0	And	0	And	1	Then	Left
14	IF	0	And	0	And	0	Then	Right
15	IF	1	And	0	And	0	Then	Right
16	IF	0	And	0	And	0	Then	Left
17	IF	1	And	0	And	0	Then	Right
18	IF	0	And	0	And	0	Then	Right
19	IF	1	And	0	And	0	Then	Left
20	IF	1	And	0	And	0	Then	Left
21	IF	1	And	0	And	0	Then	Left
22	IF	1	And	0	And	0	Then	Left
23	IF	1	And	0	And	0	Then	Left
24	IF	1	And	0	And	0	Then	Left
25	IF	1	And	1	And	1	Then	Right
26	IF	0	And	0	And	0	Then	None
27	IF	1	And	1	And	1	Then	None

3. Defuzzification Process

The crisp output action value is calculated using Sugeno action. Thus for linear velocity Vy, two sets of action "Right (R) and Left (L)" which are related to speed of (-200 mm/s, 200 mm/s) respectively are chosen after many trails as the best velocity selected values as in Fig.10.

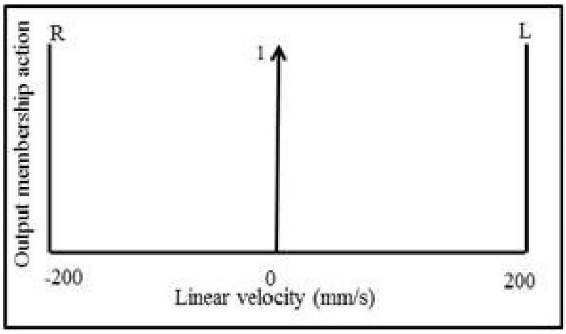


Fig.10 Linear velocity (Vy) defuzzification process

The overall resultant system block diagram is illustrated as in Fig.11. While the algorithmic procedure steps are discussed as below along with its related flowchart of Fig.12.

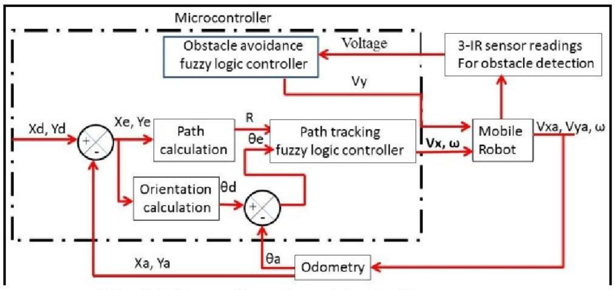


Fig.11 Overall system block diagram

The algorithm steps are:

- Step 1**:** Start.
- Step 2: Input Xd and Yd coordinates of the desired position.
- Step 3: If one of the measured IR sensor signal is more than 0.9 volt, this means there is an obstacle, thus obstacle avoidance fuzzy logic controller must be applied, else go to Step 4.
- Step 4: Apply path tracking fuzzy logic controller.
- Step 5: Move towards the target and check if the current position meets the desired one. If it is true go to Step 6, else go to Step 3.
- Step 6: stop.

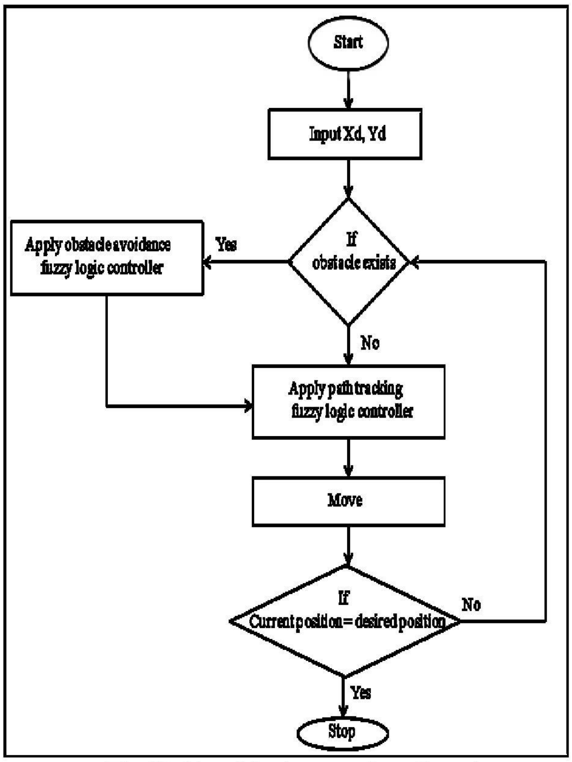


Fig.12 Algorithmic procedure flowchart

IV.

V. Experimental Results

As a challenge to the fuzzy logic controller ability in moving Robotino® safely along its drawn trajectory, U-shape obstacle has been put in the way of the mobile robot. Fig.13 shows the schematic diagram of Robotino® behavior to reach its destination avoiding this obstacle with the following steps of movements taken based on the two fuzzy controllers.

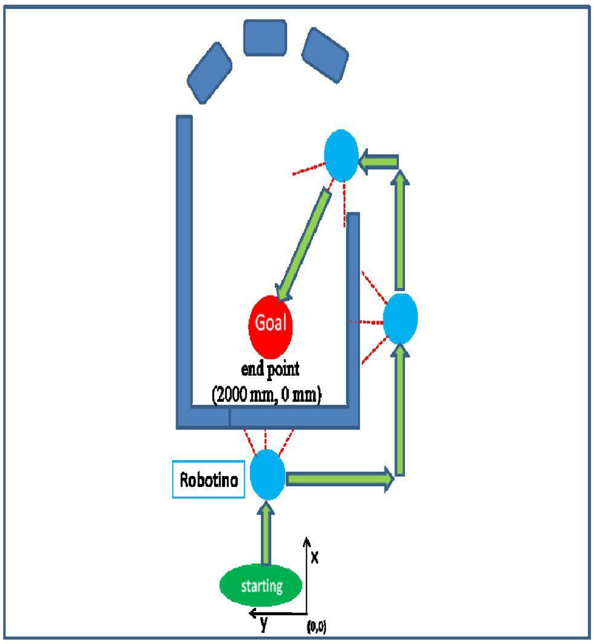


Fig.13 U-shape obstacle environment

Step 1: Movement takes place at X-direction with no change in Y one.

Step 2: Robotino® detects an obstacle not far from 400 mm. Thus an action is taken to move to the right as planned before for priority i.e. change in Y direction only.

Step 3: When no obstacle is detected, Robotino® corrects its rotational angle to move towards the destination from its instant position.

Step 4: Algorithm still modifies Robotino® position in the same manner as discussed above until reaching its desired position with almost zero steady state error with time response is as shown in Fig.14 where 5222 samples acquired using a period of 54 seconds, therefore the sampling time was 10 ms

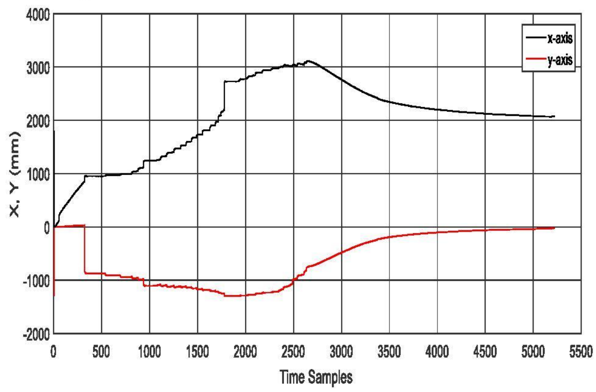
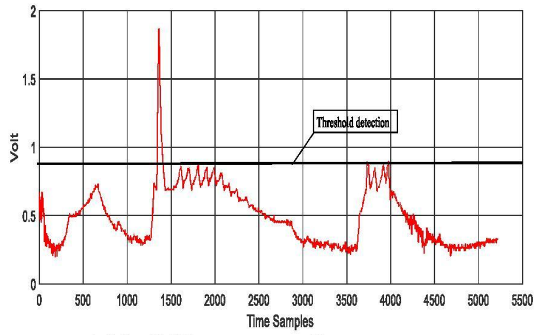
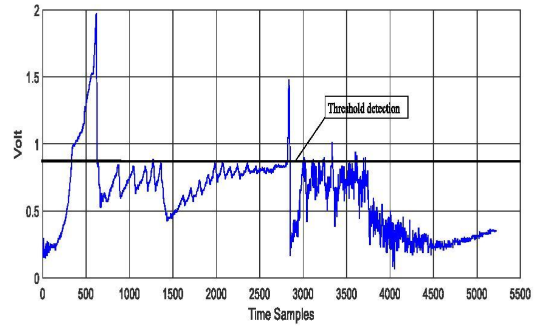


Fig.14 Robotino® time response in avoiding U-shape obstacle

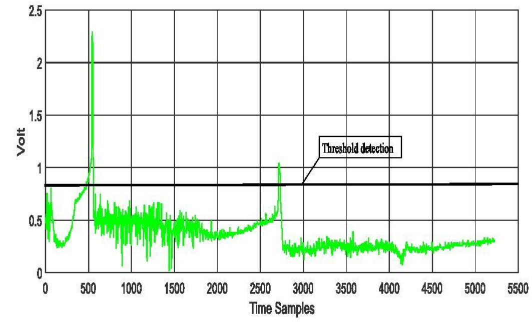
The engineering point of view requires a study to the measured and actuating signals that led to the pre-described results. As for measured analog voltages as in Fig.15 a, b and c) which is drawn using the same scale as Fig.14. A bold black line at 0.9 volt is drawn to indicate this threshold.



(a) Left IR-sensor readings



(b) Front IR-sensor readings



(c) Right IR-sensor readings

Fig.15 a, b and c Robotino® IR sensors readings for U-shape obstacle case

The conclusion is directly extracted when an obstacle is detected i.e. IR-sensor readings is greater than 0.9 volt. The synchronized motor's movements "left, right, back" regarding this case is as shown in Fig.16, which indicates that all motors work to drive Robotino® to the right direction as programmed to avoid the obstacle. When this will finish, the controller sends the required signals to move Robotino® forward (left and right motors work in different direction while the back motor in OFF-state).

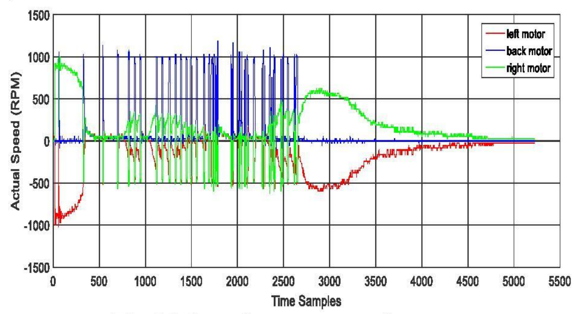


Fig.16 Actual motors speeds

VI. CONCLUSION

Many important points can be concluded out of this work as below:

- A comprehensive study to the mobile robot path tracking issue through literature survey, understanding the characteristics of Robotino® along with that of fuzzy logic, all these help much in the design and implementation of the proposed two fuzzy controllers.
- Fuzzy logic controller with 153-fuzzy rules has been designed to control Robotino® path tracking. It receives two inputs, the distance and orientation errors, so when they are properly controlled Robotino® moved towards its predefined path in a controllable manner. The fuzzy actions based on Sugeno fuzzy algorithm are used to control both the linear velocity in x-direction along with the angular velocity.
- To ensure Robotino® safe navigation, the other fuzzy-logic controller has been designed and successfully implemented with 27-fuzzy production rules. This helped Robotino® to detect and avoid obstacles not far from 40 cm., that is because of the 3-IR sensors feature used for this purpose.
- Three IR-sensor out of the nine available have been used to detect obstacles at left, front and right direction of Robotino®. Their readings have been fed to the obstacle avoidance fuzzy logic controller as a crisp voltage inputs fuzzified into 3-fuzzy set each. Its action based on Sugeno fuzzy algorithm used to control linear Robotino® velocity at y-direction.
- The effectiveness of the two fuzzy controllers are tested successfully using real-time experiment of U-shape obstacle environment. Many helpful data are used to represent the results such as (time response, IR-sensor readings, motors and wheel speeds, which are of high importance to extract meaningful information helped in the evaluation of proposed fuzzy controllers responses.
- Matlab simulink has been proved its effectiveness capabilities and the ease of use features in developing the overall system design. Some limitations has been found and solved regarding the compatibility with that of Robotino® software.

VII. ACKNOWLEDGMENT

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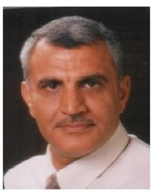

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