TYPE-2 FUZZY BEHAVIOR BASED NAVIGATION METHOD FOR MOBILE ROBOT

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Abstract: *This paper proposes an application of interval type-2 fuzzy logic controllers (IT2FLC) for the design of autonomous mobile robot behaviors. Fuzzy systems based type-2 fuzzy membership functions with their imprecise boundaries can overcome uncertainties in real applications by using membership values instead of a crisp number in Type-1 fuzzy membership function. The proposed fuzzy controllers are used to infer actions for robot movement based behaviors: goal seeking, obstacle avoidance and wall-following. The obtained simulation results show the effectiveness of these behaviors for autonomous robot navigation. The results are discussed and compared.*

Key words: *Type-2 Fuzzy Controller, Behavior, Navigation.*

1. Introduction

Mobile robot navigation is the task to define the motion control values allowing the robot to move from the start point to the final one without human actions [1]. The complex environment needs more treatments to guide the mobile robot autonomously without any collision within the existed objects and obstacles [1][2]. Behavior-based navigation approaches [3] present successful tools of structuring the global navigation task into small systems. The principle consists to subdivide the navigation task into basic behaviors: goal seeking, obstacle avoidance, wall following, target pursuing, avoiding dynamic objects,…etc. Designing these behaviors becomes a more difficult with increasing of uncertainties and measurements [2][4].

Fuzzy logic controllers (FLC) have the capacity to overcome these uncertainties. They represent robust approaches used for autonomous mobile robot navigation and for representing behaviors [5][6][7]. Type-1 fuzzy logic system uses crisp and precise type-1 fuzzy sets. However, type-2 fuzzy logic systems present important tools to improve the system performances.

Type-2 fuzzy sets create a new generation of fuzzy logic controllers [8] and offer an opportunity to model some levels of uncertainty which type-1 fuzzy logic system cannot do. The additional dimension of type-2 membership function may give a better representation of uncertainty than type-1 [9][10]. IT2FLC can focus on imprecision and give a good representation of knowledge in the form of *IF….THEN* fuzzy rules. This imprecision that T1FLC represent is in the form of membership functions, or linguistic values, and it is a powerful tool which is still widely used [11].

Fuzzy systems applications are found in robotics and automotive, where improvements over traditional controllers have been achieved [5][7][11]. Type-2 fuzzy logic systems represent interesting tools to be applied to the problem of motion planning and navigation since the output varies smoothly as the input changes.

In papers [11] and [12], reviews on the applications of Interval Type-2 Fuzzy Logic are presented and discussed for different control problems, especially in robotic field. Authors in paper [13] have proposed intelligent control for a mobile robot based on Mamdani type-2 fuzzy logic system for obstacle avoidance and wall following. In paper [14], an interval type-2 fuzzy logic was proposed to control a robot for tracking a mobile object. A Type-2 FLC was designed too in [15] for mobile robot navigation in dynamic environments with a hierarchical structure by reducing the number of rules and increasing the speed. Type-2 Takagi-Sugeno FLC was developed for modular and reconfigurable robots for tracking in [16].

For tuning and adjusted fuzzy controller parameters, some authors apply intelligent algorithms inspired from nature properties as: directed Artificial Bee Colony Algorithm [17], a reinforcement ant optimized fuzzy controller was studied in paper [18] for the wall-following behavior. A hybrid algorithm for tuning parameters in Fuzzy Models is shown in paper [19]. In the paper [20], the authors have proposed an adaptive charged system search for optimal tuning of fuzzy controllers. Another algorithm is the Combined Ant Colony Optimization and Simulated Annealing Algorithm is applied to assess stability and fault-proneness based on internal software quality attributes in [21]. In paper [22], an overview is presented on fault diagnosis and nature-inspired optimal control of industrial process applications. Comparison between type-1 and type-2 FLCs is an interesting research topic [23]. An extension of T2FLC is the Generalized Type-2 Fuzzy Logic System. In the paper [23] is used for controlling a mobile robot and compared with IT2FLC and T1FLCs.

From fuzzy logic theory, T1FLC is much faster and easier to design than T2FLC in real time applications, but lacks resilience to noise, although it does support some level of uncertainty. IT2FLC although is more computationally complex than T1FC, and less prone to the presence of external perturbations.

In our previous paper [6], we have applied type-1 fuzzy logic systems for de design of mobile robot behavior. Whereas, in the present paper, considered to the advantages of T2FLC mentioned above, we will show an application of Takagi-Sugeno IT2FLC for mobile robot navigation and designing autonomous behaviors. In this paper, we have shown deeply that the proposed controllers are more efficient in terms of smooth and optimal paths of the robot. This is significant because this approach deals with treatment of uncertainties in robot navigation task. In this work, compared with others papers, we have studied the three main behaviors of the robot: goal seeking, obstacle avoidance and wall-following.

The paper is organized as follows: in section 2, we will introduce a brief about type-2 fuzzy logic control. Section 3 presents the fuzzy behavior based navigation with the model of the used mobile robot. In section 4, we will explain the elaborated robot behaviors. Section 5 shows the obtained simulation results of robot navigation. A comparison between type-1 and type-2 FLCs will be presented. Section 6 concludes this paper.

2. Type-2 Fuzzy Logic Controller

Type-2 fuzzy logic system uses the same notions as used in a type-1 fuzzy logic controller as: fuzzification, rule-base, inference [9][10]. The only difference is in the block of output processing as depicted in Fig.1. It is composed of a type reducer and defuzzification parts. This difference is mainly associated with the form of the membership functions, where type-reducer is used to the added degree in type-2 membership functions [8][10]. The universe of discourse of variables is characterized by a membership function which can be referred as a secondary set.

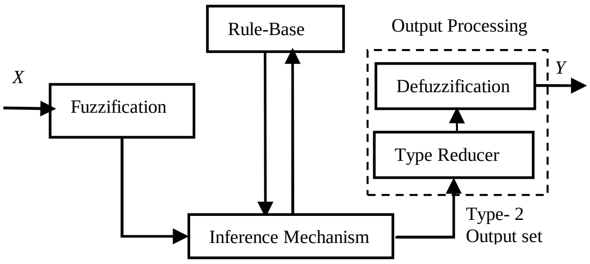

Fig. 1. Type-2 fuzzy logic System

For a first order type-2 Takagi-Sugeno (TS) fuzzy logic with M rules, p inputs ($x_1 \in X_1,...x_p \in X_p$) and one output ($y \in Y$). The r^{th} rule can be expressed as:

$$\text{IF } x_1 \text{ is } \tilde{F}_1^r \text{ and } x_2 \text{ is } \tilde{F}_2^r \text{ and...and } x_p \text{ is } \tilde{F}_i^r, \quad THEN\ y^r = c_0^r + c_1^r x_1 + ... + c_p^r x_p \tag{1}$$

The firing strength of the i^{th} rule is expressed by the following equations [8][10] :

$$\begin{aligned} W^i(x') &= [\underline{w}^i(x'), \overline{w}^i(x')] \\ \underline{w}^i &= \underline{\mu}_{\tilde{F}_l^i}(x_1) * ... * \underline{\mu}_{\tilde{F}_p^i}(x_p) \\ \overline{w}^i &= \overline{\mu}_{\tilde{F}_l^i}(x_1) * ... * \overline{\mu}_{\tilde{F}_p^i}(x_p) \end{aligned} \tag{2}$$

The output is an interval type-1 set calculated by:

$$\begin{aligned} Y(Y^1,...,Y^M, W^1,...,W^M) &= [y_l, y_r] \\ &= \int_{y^1} ... \int_{y^M} \int_{w^M} ... 1 / \frac{\sum_{i=1}^{M} w^i y^i}{\sum_{i=1}^{M} w^i} \end{aligned} \tag{3}$$

Where $y_i \in Y^i$, and $Y^i = [y_l^i, y_r^i]$, $(i=1…M)$, y_l and y_r are calculated using the equations 4 and 5.

$$y_l = \frac{\sum_{i=1}^{M} w_l^i y_l^i}{\sum_{i=1}^{M} w_l^i}, \quad y_r = \frac{\sum_{i=1}^{M} w_r^i y_r^i}{\sum_{i=1}^{M} w_r^i} \tag{4}$$

The final output to be applied to the system is:

$$y = (y_l + y_r)/2 \tag{5}$$

3. Type-2 Fuzzy Behavior Based Navigation

A. Navigation Structure

The principle is to decompose the global navigation task into small sub tasks called: *behaviors*. These behaviors can be: goal seeking, obstacle avoidance, wall-following, target pursuing,... The control structure contains these primitive behaviors considered as type-2 fuzzy controllers composed of a set of *IF-THEN* fuzzy logic rules in order to achieve a desired objective [3][6]. The behaviors are supervised using a coordination system to select the appropriate actions transmitted to actuators (Fig. 2). This divide approach makes the system modular and well performed [3].

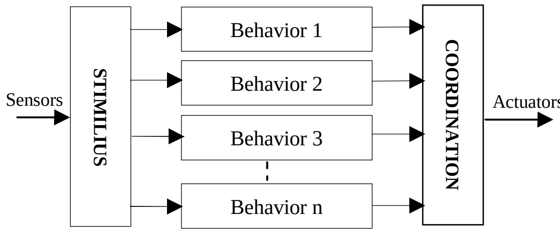

Fig. 2. Behavior based navigation

B. The Used Mobile Robot

The mobile robot used in this study is a cylindrical mobile platform depicted in Fig.3. It is assumed that this vehicle moves without slipping on a plane, i.e., there is a pure rolling contact between the wheels and the ground. The kinematic model can be described by the following equations (6):

$$\begin{aligned} \dot{x}_r &= v_r \cos(\theta_r) \\ \dot{y}_r &= v_r \sin(\theta_r) \\ \dot{\theta}_r &= w \end{aligned} \qquad (6)$$

Where (x_r, y_r, θ_r) describes the robot configuration (x_r and y_r are the robot's cartesian coordinates, and θ_r is the heading angle) of the center of the axis of the wheels, with respect to a global inertial frame (O,X,Y). The control actions for robot movement are: the linear velocity (v_r) and the steering angle (α_r) calculated from the angular velocity (w).

In order to detect objects in the environment, the simulated robot is equipped by 12 ultrasonic sensors. Each sensor s_i for $(i = 1,...,12)$ gives the measured distance to the obstacle in its field of view. The sensor can give measures between (*0* and *2m*). These 12 sensors are arranged in the three sides to give (distance on front d_F, distance on the right d_R and the distance on the left d_L).

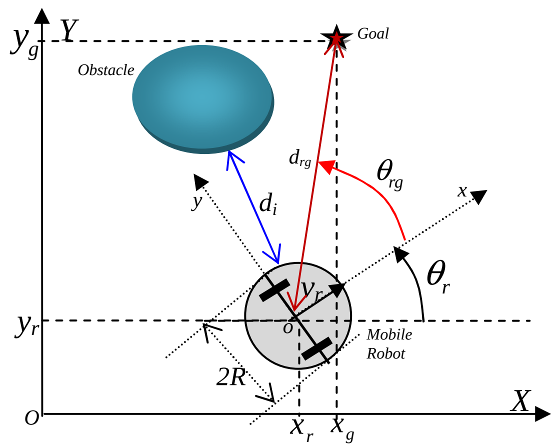

Fig. 3. The model of mobile robot

4. The Proposed Robot Behaviors

In our work, Interval type-2 Takagi-Sugeno fuzzy logic systems are used to design robot behaviors by adding uncertainties in the antecedent parts of each fuzzy rule. The consequent parts are singleton types. The r^{th} fuzzy rule base is defined as:

$$\text{IF } x_1 \text{ is } \tilde{F}_1^r \text{ and } x_2 \text{ is } \tilde{F}_2^r \text{ and...and } x_p \text{ is } \tilde{F}_i^r, \qquad (7)$$

$$\text{Then } y^r = c_0^r + c_1^r x_1 + \ldots + c_p^r x_p$$

In the inference engine, we used the steps of Takagi-Sugeno IT2FLC presented previously (equations: 2…5). Each fuzzy controller has two outputs: the steering angle and the linear velocity for motion corresponding the equation:

$$\alpha = (y_{l1} + y_{r1})/2, \text{ and } v = (y_{l2} + y_{r2})/2 \qquad (8)$$

The proposed fuzzy navigators are based on the design of the three basic robot behaviors: a Goal Seeking Behavior (GSB), an Obstacle Avoidance Behavior (OAB) and a Wall Following Behavior (WFB). In our work, these controllers are conceived based on: human expertise, the robot navigation parameters and depending to desired tasks and objectives.

A. Goal Seeking Behavior (GSB)

The objective of the goal seeking task is to control the mobile robot to go on the direction of the goal. The used block diagram of the robot fuzzy controller is shown in Fig. 4. The elaborated type-2 TS fuzzy controller infers the appropriate control actions (α_g and v_g) to reach the desired goal. The inputs variables (d_{rg} and θ_{rg}) are computed by the calculation module using the equations (8, 9 and 10), and based on the measures of the localization sensor (odometry). These variables are fuzzified by the membership functions depicted in Fig.5 and Fig.6. We used triangular membership functions for linguistics terms with uncertainties. Whereas the output actions: v_g and α_g are represented by singletons shown in Fig.7 and Fig.8 respectively. Where: R is the radius of robot platform ($R=0.25m$), v_{max} is the maximum velocity of mobile robot ($v_{max}=0.2m/s$).

$$d_{rg} = \sqrt{(x_g - x_r)^2 + (y_g - y_r)^2} \qquad (9)$$

$$\theta_d = arctg\left(\frac{y_g - y_r}{x_g - x_r}\right) \qquad (10)$$

$$\theta_{rg} = \theta_d - \theta_r \qquad (11)$$

The linguistic labels used to define fuzzy membership functions are mentioned below of each variable. The fuzzy rule-base used to define this autonomous behavior is presented also in table. I.

Each fuzzy rule is at the form as follows:

IF d_{rg} *is* A^i_1 *and* θ_{rg} *is* A^i_2 *THEN* v_g *is* B_1^i *and* α_g *is* B_2^i

Where $i=1…N$, and N is the number of fuzzy rules ($N=28$), $A^i_1…A^i_2$ are the input fuzzy sets, B^i_1 and B^i_2 are the membership functions of the control actions.

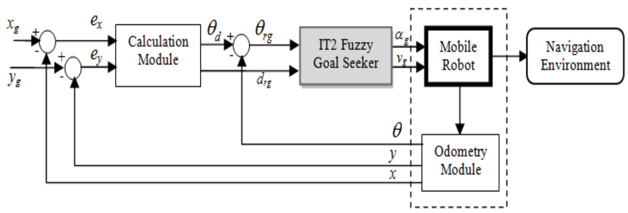

Fig. 4. Structure of Type-2 Fuzzy Goal seeker

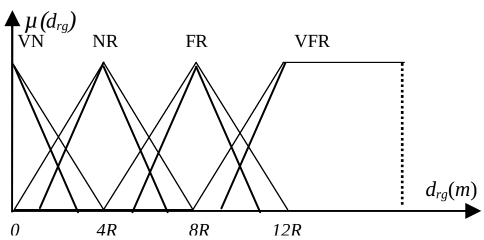

Fig.5. The membership functions of the distance d_{rg} (**VN**: *Very Near*, **NR**: *Near*, **FR**: *Far*, **VFR**: *Very Far*)

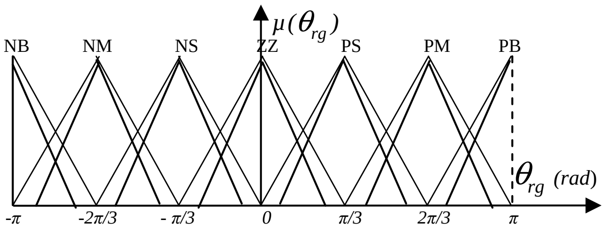

Fig.6. The membership functions of the angle θ_{rg}

(***NB**: Negative Big, **NM**: Negative Medium, **NS**: Negative Small, **ZZ**: Zeros, **PS**: Positive Small, **PM**: Positive Medium, **PB**: Positive Big*)

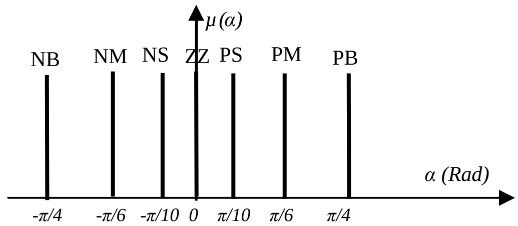

Fig.7. The membership functions of the steering angle (***NB**: Negative Big, **NM**: Negative Medium, **NS**: Negative Small, **ZZ**: Zeros, **PS**: Positive Small, **PM**: Positive Medium, **PB**: Positive Big*)

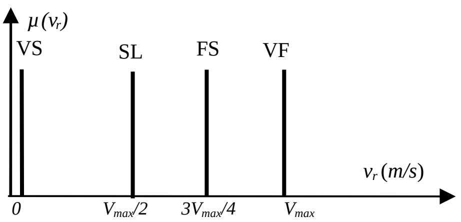

Fig.8. The membership functions of the robot velocity

(***VS**: Very Slow, **SL**: Slow, **FS**: Fast, **VF**: Very Fast*)

Table. I. Fuzzy Rules for the Goal Seeking Behavior

Actions: velocity, Steering		*Distance Robot-Goal*			
		VN	**NR**	**FR**	**VFR**
Angle Robot-Goal	**NB**	VS	VS	SL	SL
		PB	PB	PB	PB
	NM	VS	VS	SL	FS
		PM	PM	PM	PM
	NS	VS	SL	FS	VF
		PS	PS	PS	PS
	ZZ	VS	SL	FS	VF
		ZZ	ZZ	ZZ	ZZ
	PS	VS	SL	FS	VF
		NS	NS	NS	NS
	PM	VS	VS	SL	FS
		NM	NM	NM	NM
	PB	VS	VS	SL	SL
		NB	NB	NB	NB

B. Obstacle Avoidance Behavior (OAB)

This behavior consists to control the robot safely in its environment without collisions with the surrounded objects and obstacles. The global navigation task is achieved by activating the two behaviors: goal seeking and obstacle avoidance.

The fuzzy obstacle avoider uses the three measured distances in three sides (d_R, d_L and d_F) as inputs to carried out the steering angle (α_o) and the robot linear velocity (v_o). The structure of the proposed robot navigator is shown in Fig. 9. The calculation module computes the inputs of the fuzzy controllers: (d_{rg} and θ_{rg} based on equations 9-10-11) and the measured distances on three sides. After a treatment process, the control actions are inferred, and the values that will be applied by the robot are selected using a coordination block (switch): actions to goal seeking if the environment is free, or avoiding collisions if there is one or more nearest obstacles.

The fuzzy sets used to fuzzified the distances are depicted in Fig 10. We used triangular and trapezoidal membership functions due the fact are easy to implement computationally. The fuzzy *If-Then* rules considered are presented in table II. It contains 27 rules. Each fuzzy rule at the form of:

$$\text{IF } d_R \text{ is } A^i_1 \text{ and } d_L \text{ is } A^i_2 \text{ and } d_F \text{ is } A^i_3 \quad \text{THEN } v_o \text{ is } B_1^i \text{ and } \alpha_o \text{ is } B_2^i \qquad (12)$$

Where: A^i_1, A^i_2 and A^i_3 represent one of the three fuzzy sets presented in Fig. 10 (*NR*, *MD* or *FR*). B_1^i *and* B_2^i are the singletons of the output actions (Fig. 7 and Fig. 8).

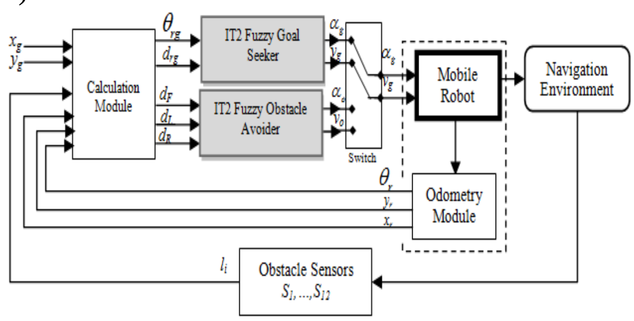

Fig. 9. Structure of Type-2 Fuzzy Navigator

Table. II. Fuzzy Rules for the Obstacle Avoidance Behavior

d_F	d_L	d_R		v_o	α_o
NR	**NR**	**NR**	Actions : velocity, Steering	*VS*	*PB*
		MD		*VS*	*PB*
		FR		*VS*	*PB*
	MD	**NR**		*VS*	*PB*
		MD		*VS*	*PB*
		FR		*VS*	*PM*
	FR	**NR**		*VS*	*NB*
		MD		*VS*	*NB*
		FR		*VS*	*PB*
MD	**NR**	**NR**		*VS*	*PB*
		MD		*VS*	*PB*
		FR		*SL*	*PM*
	MD	**NR**		*SL*	*PB*
		MD		*VS*	*PB*
		FR		*SL*	*PM*
	FR	**NR**		*SL*	*NM*
		MD		*SL*	*NM*
		FR		*SL*	*PM*
FR	**NR**	**NR**		*SL*	*ZZ*
		MD		*SL*	*PS*
		FR		*FS*	*PS*
	MD	**NR**		*SL*	*NS*
		MD		*SL*	*ZZ*
		FR		*FS*	*PS*
	FR	**NR**		*FS*	*NS*
		MD		*FS*	*NS*
		FR		*VF*	*ZZ*

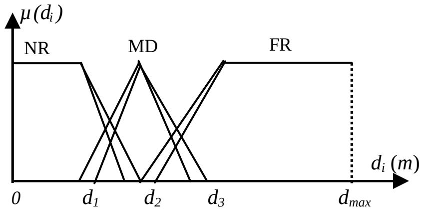

Fig.10. Membership functions of the distances to obstacles (*NR: Near, MD: Medium, FR: Far*)

C. Wall-Following Behavior (WFB)

The role of this behavior is to control the robot movement at a safe close distance to the nearest right or left wall. Since noise-elimination is important for this behavior, the antecedents are type-2 fuzzy sets and the consequents are fuzzy singletons for both variables: α_w and v_w (as shown in Fig. 7 and Fig.8). The designed fuzzy controller uses the distance values to walls as inputs. Fig. 11 represents the fuzzy sets used to fuzzify the distances (d_R, d_L and d_F). The control structure is shown in Fig. 12.

In table III, we present the eight fuzzy rules deduced from human expertise to accomplish this task. Each fuzzy rule takes the form of:

IF d_R *is* A^i_1 *and* d_L *is* A^i_2 *and* d_F *is* A^i_3
THEN v_w *is* B_1^i *and* α_w *is* B_2^i (13)

Where: A^i_1, A^i_2 and A^i_3 represent one of the two fuzzy sets (Near or Far). B_1^i *and* B_2^i are fuzzy singletons of the output actions.

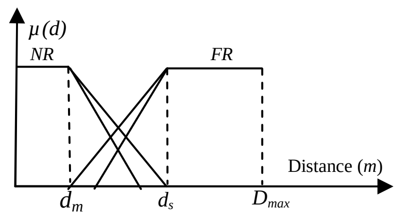

Fig. 11. Membership functions of the distances to walls (*NR: Near, FR: Far*)

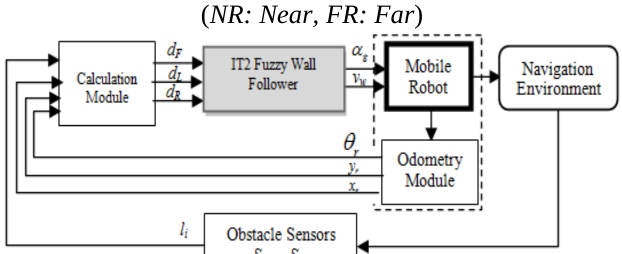

Fig. 12. Structure of Type-2 Fuzzy Wall Follower

Table. III. Fuzzy Rules for the Wall Following Behavior

Actions: Steering velocity			*Distance d_L*			
			NR		**FR**	
			Distance d_F			
			NR	**FR**	**NR**	**FR**
d_R	**FR**	α_w	*PB*	*PS*	*NB*	*PM*
		v_w	*VS*	*FS*	*VS*	*FS*
	NR	α_w	*NB*	*ZZ*	*NB*	*NS*
		v_w	*VS*	*FS*	*SL*	*SL*

5. Simulation and Results

This study consists to equip the robot with the capability of goal seeking, obstacles avoidance and wall-following without being stuck in local minima and without collision with obstacles. For this purpose, we used the mobile robot model presented in section 3 and the proposed fuzzy navigators presented in section 4. Simulation has been done by using Visual-basic language and MoboSim simulator.

A. Results of Navigation

In this section, to verify the effectiveness of the elaborated behaviors, we will present examples of autonomous mobile robot paths.

The simulation results of the goal seeking behavior are given in Fig. 13 using the designed fuzzy controller. It presents the robot paths for different initial positions of the robot (*s1,.., s7*) for a fixed goal position. In this simulation, we consider different start values of (x_r, y_r, θ_r) and initial control actions $(\alpha_g = 0,\ v_g = 0)$. As depicted, in all cases, the robot moves toward the desired point correctly by executing smoothness actions. As seems, after some steps of steering in the first time, the robot goes toward the goal. The robot velocity decreases at time when it approaches the target. The robot stops when it reaches the goal coordinates. The proposed type-2 fuzzy controller behaves correctly and well performed to accomplish this task. It has the advantage to give the robot with a certain degree of intelligence and autonomy.

In the presence of obstacles and objects, the mobile robot must have the capability to avoid collisions. The robot executes the actions of obstacle avoidance fuzzy controller type-2 in order to move toward the final destination safely without any collision with the surrounding obstacles. Fig. 14 illustrates the paths of the obtained behavior. With different start positions (S_1 to S_7), the robot navigates without collision with the detected obstacles in three sides of motion (front, on right and on left). The mobile robot can move autonomously toward the desired goal correctly by executing the actions generated the goal seeking controller (α_g and v_g). When it detects one or more obstacles, the type- 2 fuzzy obstacle avoider calculates the appropriate control actions of steering and velocity (α_o and v_o) to move autonomously by avoiding collision. By activating the two fuzzy controllers (GSB and OAB), the results approve the smoothness and the stability of the designed fuzzy controllers. They have a good level of performances to realize the mobile robot navigation task for any start position.

The obtained results for wall following behavior with different types of environments are shown in Fig. 15. This figure presents the paths of the mobile robot to follow walls in the environment. The task consists to move autonomously and safely in its environment by following the right walls.

As depicted, the robot is able to navigate in its environment autonomously without collision. It keeps a constant and a safe distance to walls. The designed fuzzy robot behavior is satisfactory in all cases with security.

These presented simulation results illustrate that the elaborated type-2 fuzzy controllers prove a high effectiveness for autonomous mobile robot motion (goal seeking, obstacle avoidance and wall-following).

Interval Type-2 fuzzy controllers are interesting tools to overcome the uncertainties in measurement and in designing robot behaviors. Using knowledge based human driver at forms of linguistic expressions, these fuzzy systems can control the robot easily and effectively with a high level of intelligence and autonomy.

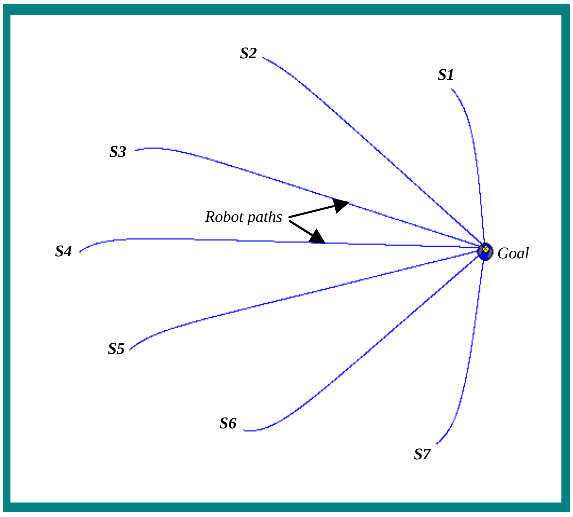

Fig.13. Results of Goal Seeking Behavior

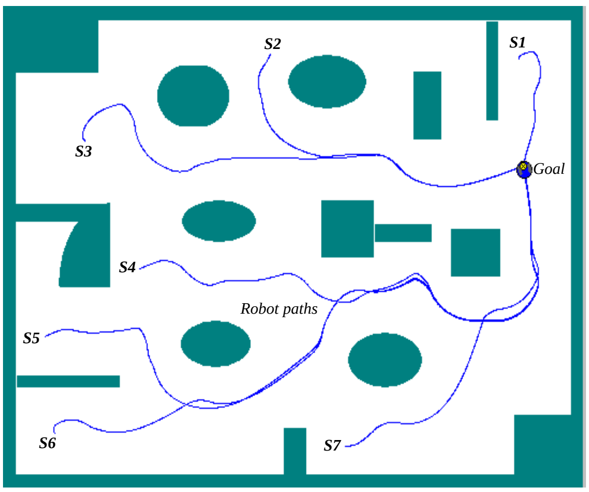

Fig.14. Results of Navigation with Obstacle Avoidance Behavior

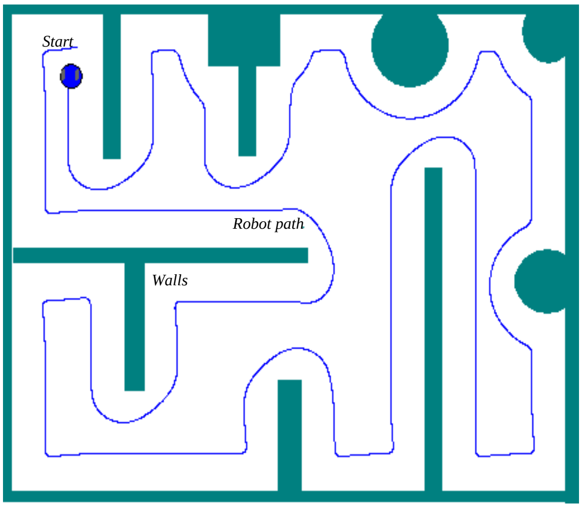

Fig.15. Results of Wall following Behavior

B. Comparison between type-1 and type-2 FLCs

Fuzzy Sets are well known for their resilience to noise, especially IT2FLC when compared to a T1FLC, depending on the level of uncertainty which wants to be handled. IT2FLC handles uncertainty directly into its system, whereas a T1FLC cannot. Although it follows the same logic as a T1FLC with a minor difference.

In this section, we will present a comparison between TS type-1 and TS type-2 fuzzy logic systems for the elaboration of a goal seeking behavior. The two controllers are compared in the same conditions with the same rule-base. The robot is simulated at the same initial positions. Fig. 16 shows the paths of the mobile robot generated by T1FLC and T2FLC (in red and blue colors respectively). For a fixed target coordinates ($x_g = 16.6$, $y_g = 15.6$) and different start positions of the mobile robot as depicted in table IV. From the robot paths, it clearly demonstrates that in all cases the robot moves toward the goal effectively. The behavior is accomplished successfully using the two types of controllers, but some differences are observed on the paths. We have shown deeply that the proposed T2 FLC is more efficient in terms of saving time and smooth trajectories. The task is faster when we use T1FLC than the IT2FLC as demonstrated in the table by measuring the necessary time to reach the goal due to the computationally process needed to infer the control actions. But this behavior is more satisfactory and precise using the second fuzzy approach. Interval type-2 fuzzy sets overcome uncertainties that can exist, but the studied behavior has less degree of uncertainties than other behaviors.

Table. IV. Simulation Values

Position	x_r (m)	y_r(m)	θ_r (rad)	Time of T1FLC	Time of IT2FLC
S1	5.50	6.00	0	1m59,4s	2m47,9s
S2	5.50	9.50	0	1m48,9s	2m34,4s
S3	5.50	12.50	0	1m42,8s	2m25,6s
S4	5.50	15.50	0	1m40,0s	2m41,0s

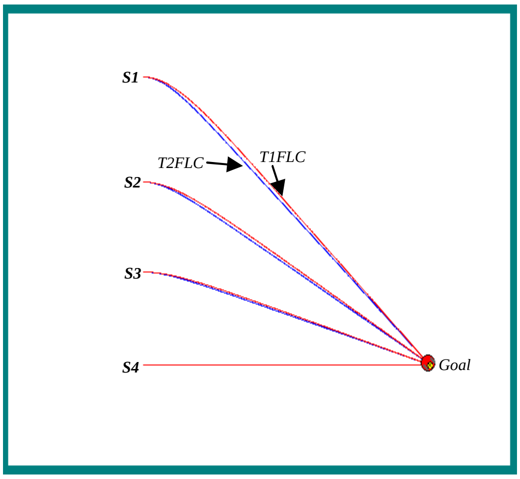

Fig.16. Comparison between type-1 and type-2 FLCs

6. Conclusion

In this paper, we have applied interval type-2 Takagi-Sugeno fuzzy controllers for the autonomous navigation of a mobile robot in unknown environments. The navigation task is subdivided into basic behaviors considered as controllers: goal seeking, obstacle avoidance, wall following. These behaviors allow the robot to move safely without collision in order to reach the final target. The obtained results show the efficiency of the elaborated systems to handle uncertainties.

In future work, we will compare this type of control with the basic type-1 fuzzy logic systems for designing other behaviors of mobile robot. The interest will be given to the application of Generalized Type-2 Fuzzy Logic Systems (GT2FLS).

References

1. S. G. Shuzhi, F. L. Lewis, *Autonomous Mobile Robots, Sensing, Control, Decision, Making and Applications*, CRC, Taylor and Francis Group, 2006.
2. A. V. Topalov, *Recent Advances in Mobile Robotics*, InTech Publication, Croatia, 2011.
3. R. Brooks, *A Robust Layered Control System for a Mobile Robot*, IEEE Journal on Robotics and Automation, Vol. 2, No. 1, pp.4-23, 1986.
4. P. G. Zavlangas and S. G. Tzafestas, *Motion Control for Mobile Robot Obstacle Avoidance and Navigation: A Fuzzy Logic-Based Approach*, Systems Analysis Modeling Simulation, Vol. 43, No. 12, pp. 1625-1637, 2003.
5. X. S. Yang et al, *An Embedded Fuzzy Controller for a Behavior-Based Mobile Robot with Guaranteed Performance*, IEEE Transaction on Fuzzy Systems, Vol. 12, no. 4, pp. 436-446, 2004.
6. L. Cherroun and M. Boumehraz, *Fuzzy Behavior Based Navigation Approach for Mobile Robot in Unknown Environment*, Journal of Electrical Engineering, Vol. 13, No. 4, pp. 284-291, 2013.
7. R. E. Precup and al, *A Survey on Industrial Applications of Fuzzy Control*, Computers in Industry, Vol. 62, No. 3, pp. 213-226, 2011.
8. H. Hagras, *Type-2 FLCs: A New Generation of Fuzzy Controllers*, IEEE Computational Intelligence Magazine, Vol. 2, No. 1, pp.30-43, 2007.
9. J. M. Mendel, R. I. John and F. Liu. *Interval Type-2 Fuzzy Logic Systems Made Simple*. IEEE Transactions on Fuzzy Systems, Vol. 14, No. 6, pp. 808-821, 2006.
10. N. Karnik, J. Mendel and Q. Liang, *Type-2 Fuzzy Logic Systems*, IEEE Transactions on Fuzzy Systems, Vol. 7, No. 6, pp. 643-658, 1999.
11. K. Tai and al, *Review of Recent Type-2 Fuzzy Controller Applications*, Algorithms, 9, 39, 2016.
12. O. Castillo, P. Melin, *A Review on Interval Type-2 Fuzzy Logic Applications in Intelligent Control*, Information Sciences, Vol. 279, pp. 615-631, 2014.
13. N. Baklouti, R. John and A. Alimi. *Interval Type-2 Fuzzy Logic Control of Mobile Robots*, Journal of Intelligent Learning Systems and Applications, Vol. 4, pp. 291-302, 2012.
14. L. Astudillo, O. Castillo, and L. Aguilar, *Intelligent Control for a Perturbed Autonomous Wheeled Mobile Robot: a Type-2 Fuzzy Logic Approach*, Nonlinear Studies, Vol. 14, No. 1, pp. 37-48, 2007.
15. H. A. Hagras, *A Hierarchical Type-2 Fuzzy Logic Control Architecture for Autonomous Mobile Robots*. IEEE Trans. Fuzzy Syst. Vol. 12, pp. 524-539, 2004.
16. M. Biglarbegian, W. Melek, J. M. Mendel. *Design of Novel Interval Type-2 Fuzzy Controllers for Modular and Reconfigurable Robots: Theory and Experiments*, IEEE Transaction on Industrial Electron. Vol. 58, pp. 1371-1384, 2011.
17. M. Kiran, O. Findik, *A Directed Artificial Bee Colony Algorithm*, Applied Soft Computing, Vol. 26, pp. 454-462, 2015.
18. C. F. Juang, C.-H. Hsu, *Reinforcement Ant Optimized Fuzzy Controller for Mobile-Robot Wall-Following Control*, IEEE Trans. Ind. Electron. Vol. 56, pp. 3931-3940, 2009.
19. Z. C. Johanyák, O. Papp, *A Hybrid Algorithm for Parameter Tuning in Fuzzy Model Identification*, Acta Polytechnica Hungarica, Vol. 9, No. 6, pp. 153-165, 2012.
20. R. E. Precup and al, *Novel Adaptive Charged System Search Algorithm for Optimal Tuning of Fuzzy Controllers*, Expert Systems with Applications, Vol. 41, No. 4, pp. 1168-1175, 2014.
21. D. Azar, K. Fayad and Daoud, *A Combined Ant Colony Optimization and Simulated Annealing Algorithm to Assess Stability and Fault-proneness of Classes based on Internal Software Quality Attributes*, International Journal of Artificial Intelligence, Vol. 14, Vo. 2, pp. 137-156, 2016.
22. R. E. Precup and al, *An Overview on Fault Diagnosis and Nature-Inspired Optimal Control of Industrial Process Applications*, Computers in Industry, Vol. 74, pp. 75-94, 2015.
23. M. A. Sanchez, O. Castillo, J. R. Castro, *Generalized Type-2 Fuzzy Systems for Controlling a Mobile Robot and a Performance Comparison with Interval Type-2 and Type-1 Fuzzy Systems*, Expert Systems with Applications, Vol. 42, pp. 5904-5914, 2015.