Control of mobile robot for trajectory tracking in the presence of external disturbance

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Abstract— **Trajectory tracking is an essential problem for autonomous mobile robot. The primary mission for every mobile robot is to move along a target trajectory in an unknown environment. In this work, a kinematic model of two wheel mobile robot for reference trajectory tracking is introduced. This paper presents the advanced technique for controlling the wheeled mobile robot based on fuzzy logic control. The proposed controller is designed on Matlab Simulink environment and is investigated when the external disturbances are introduced in the system inputs. The intelligent controller provides good solution for trajectory tracking. Simulations are presented to show the performance of the fuzzy logic controller.**

***Keywords*— wheeled mobile robot; fuzzy logic controller; moving to a point; external disturbance;**

I. INTRODUCTION

The problem of navigation for a mobile robot in which the data and the constraints are too complex, or ill-defined to establish a precise mathematical model have to be treated by approximate solutions or artificial methods such as fuzzy logic.

Current researches in this domain focus essentially on the improvement of desired skills specially the navigation task and the autonomy which means that a mobile has interaction rationally with its environment without need for a human intervention. Thus, the first task of autonomous navigation is to move along a desired trajectory [3] Also a large number of control algorithms were proposed in the path-tracking, such as adaptive controllers [3], fuzzy controllers [4], fuzzy neural networks [5], sliding mode control [6], etc.

An essential problem in autonomous navigation is the need to deal with the external disturbances and incertitude with the fact that the environment contains elements of dynamics. The techniques ability of fuzzy logic to represent linguistic terms and reliable decision making in spite of uncertainty and imprecise information makes it a very interesting solution in control mobile robot [1]-[8].

In the practical applications, mobile robot subjected to an external disturbance and noise. So, the proposed controller should be designed to be robust to cope with approximation error and external disturbances [9][10].

The principal objective of this paper is to insure the autonomous navigation of a tricycle mobile robot in the presence of bounded unknown disturbances using fuzzy logic control. So, the proposed controller has allowed the displacement of a robot of an initial position towards any desired destination while respecting its kinematic constraints and eliminating the external perturbation. Today, the mobile robots are based on the differential drive model, in which two wheels are responsible to both drive the robot and change its direction. A controller based on fuzzy logic sends the orders of the right and left angular velocity of each wheel to the mobile robot to ensure its convergence towards the target. A Mamdani type fuzzy logic controller based on the least number of memberships has been designed on Matlab Simulink environment and Fuzzy Toolbox.

The present paper is organized as follows. In section 2, we give a brief description of the mobile robot chosen type, its characteristics and its kinematic model. Then, the fuzzy logical control is presented in section 3. The simulations and conclusions are given in section 4.

II. KINEMATIC OF NONHOLONOMIC MOBILE ROBOT

In the interest of design controllers, a differential drive model is considered to calculate the kinematic equations of mobile robot [6], [11]. The object of the robot kinematic modelling is to find the velocity of the mobile robot as a function of the velocity of the two wheels and the geometric parameters of the robot in the inertial frame [17] [20] [21].This model of a non-holonomic constraint of pure rolling and without slipping based on the configuration shown schematically in Figure 1.

Where V_r means the linear velocity of right wheel, V_l means linear velocity of left wheel, d means the distance between the two wheels and *ICC* means the Instantaneous Center of Curvature.

Additionally, a robot is located by its position along the X and Y the two Cartesian coordinates and its angular orientation θ taken counter clockwise from the X-axis, which constitute the posture P [12], showed by the vector (1). The angle θ is restricted within the $[-\pi, \pi]$ range.

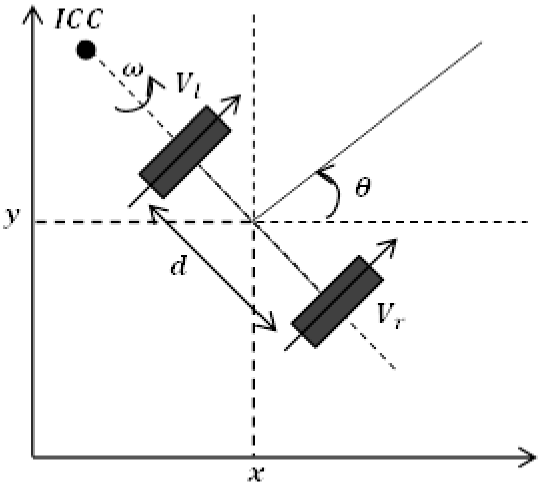

Fig. 1 Mobile Robot parameter

$$P = \begin{pmatrix} X \\ Y \\ \theta \end{pmatrix} \qquad (1)$$

The robot is controlled by the both angular velocities of the wheels (ω_r, ω_l) . Between the linear velocities (V_r, V_r) and the angular velocities (ω_r, ω_l)there are the relations [6], [13] :

$$V_r = r \times \omega_l \qquad 2)$$

$$V_l = r \times \omega_l \qquad (3)$$

Where r is the radius of a wheel, ω_r is the right wheel angular velocity and ω_l is the left wheel angular velocity. Or, the rear wheels move in the clockwise and anticlockwise directions.(Figure 2)

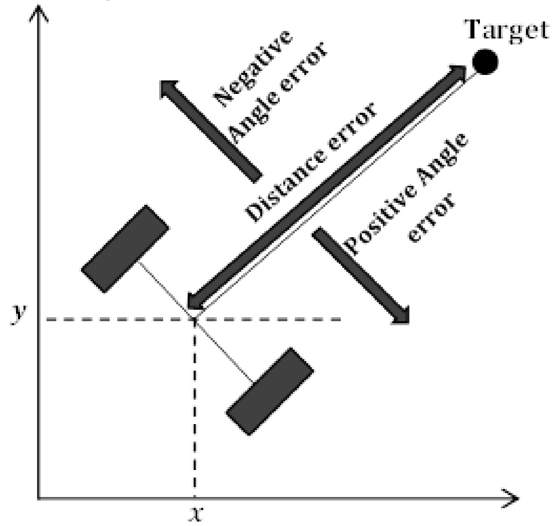

Fig. 2 Mobile Robot in Cartesian Space

The preceding equations (2) and (3) will be as follows:

$$V_r = V + \frac{d}{2} \times \omega \qquad (4)$$

$$V_l = V - \frac{d}{2} \times \omega \qquad (5)$$

Where V and ω present respectively the instantaneous linear and angular velocity of the robot about a point midway between the wheels respectively.

Adding Eq (4) and Eq (5), we find:

$$V = \frac{V_r + V_l}{2} \qquad (6)$$

Subtracting Eq (4) from Eq (5), we get:

$$\omega = \frac{V_r - V_l}{d} \qquad (7)$$

We developed the kinematic model [11] [18] obtained by a simple derivation of the posture P as shown by the system of equation (8). This model is represented in the global reference system and described the velocities of the mobile robot but not the forces or torques that cause the velocity.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V \\ \omega \end{bmatrix}$$

The vector $U = \begin{pmatrix} V \\ \omega \end{pmatrix}$ constitutes the kinematic control vector. In order to carry out path tracking control, it becomes necessary to act on the wheels of the mobile robot.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\cos\theta & \frac{r}{2}\cos\theta \\ \frac{r}{2}\sin\theta & \frac{r}{2}\sin\theta \\ \frac{r}{d} & -\frac{r}{d} \end{bmatrix} \begin{bmatrix} \omega_r \\ \omega_l \end{bmatrix} \qquad (8)$$

In this paper, we desire to definite the velocity of the wheels (V_r, V_r) for a given desired position of the mobile robot P=$(X \quad Y \quad \theta)$ These equations are used to simulate the robot in MATLAB Simulink as shown in Figure 3.

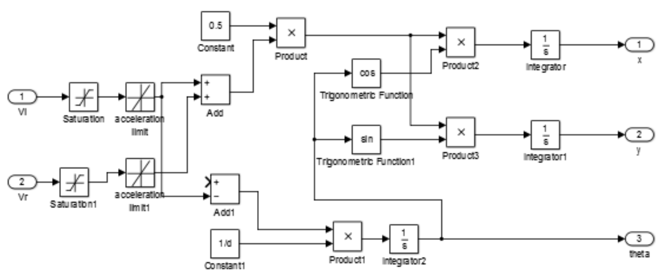

Fig. 3 Simulation model of kinematics of the mobile robot

The step response for each three parameters of the posture (x,y,θ) based on state space model is shown in Figure 4 to Figure 6.

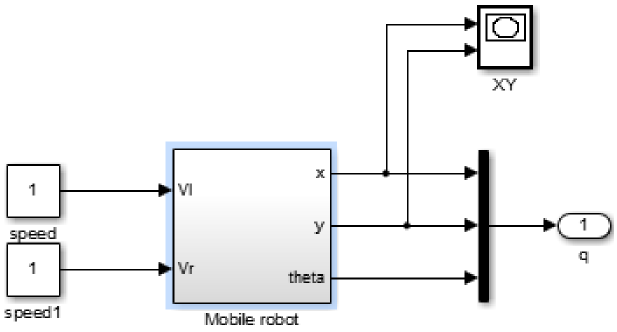

Fig 4 Simulation model of the mobile robot response of the posture

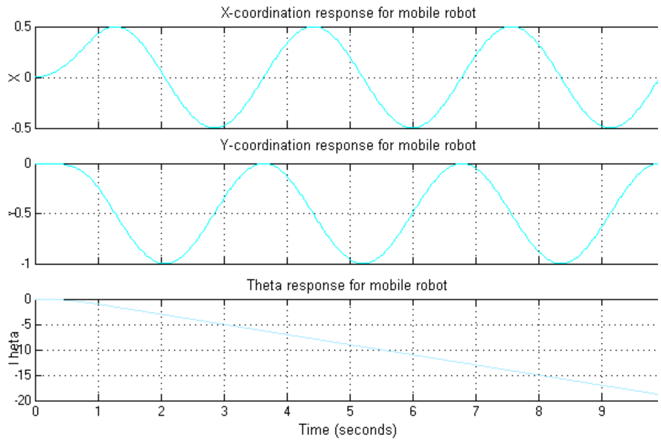

Fig. 5 The mobile robot response of the posture

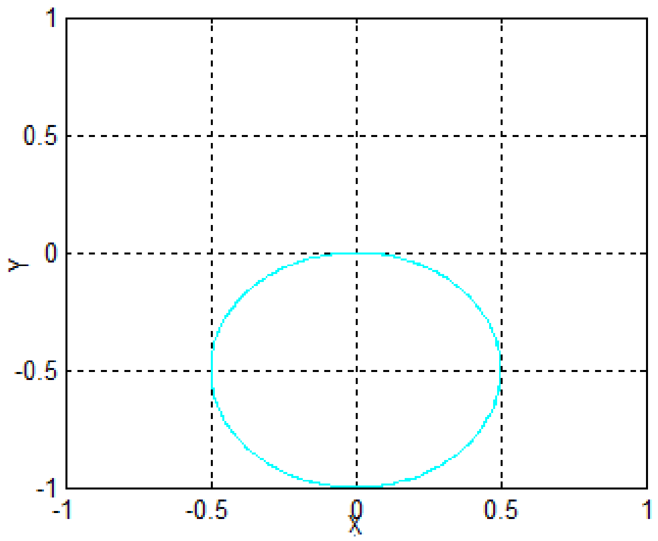

Fig. 6.Navigation of mobile robot without controller

It can be deduced from the right and the left angular velocity of the wheels of the mobile robot which follow arcs of different radius and therefore rotate at different speeds. For a fixed steering wheel angle the wheeled mobile robot moves along a circular arc.

III. Tracking Target Trajectory Using Fuzzy Logic Controller

Fuzzy Logic controller (FLC) is applied to ensure that the mobile robot can track target trajectory. The FLC used has two inputs: error in the position and error in the angle of the robot [14] [19].

Thus, the FLC has two outputs: right angular speed and left angular speed of the robot as shown in Figure 7.

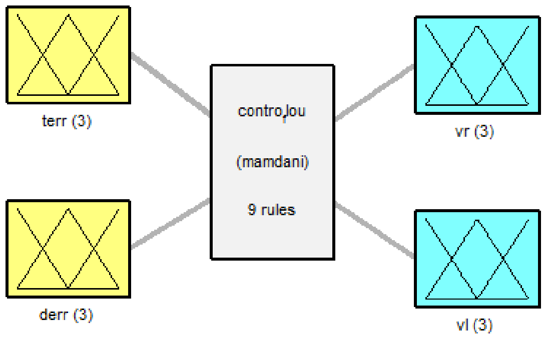

Fig. 7 Fuzzy logical control

Each control variable is normalized into three linguistic levels as presented by Table 1.

TABLE I
LINGUISTIC LEVELS FOR THE FUZZY LOGIC INPUT

Angle error	Distance error
N: Negative	Z: Zero
Z: Zero	M: Middle
P: Positive	F : Far

The fuzzy set value is set overlapping values represented by triangular shape that is called the fuzzy membership function. The triangular membership functions are used for their simplicity.

The output notation for making fuzzy rules is: Fast (F), Medium (M) and Slow (S).

The fuzzy memberships of the fuzzy variables are shown in Figure 8 to Figure 11.

Fuzzy logic rules for both the right and the left motor of the mobile robot are shown in TABLE II and III. Thus, there are 9 total rules for the two wheels.

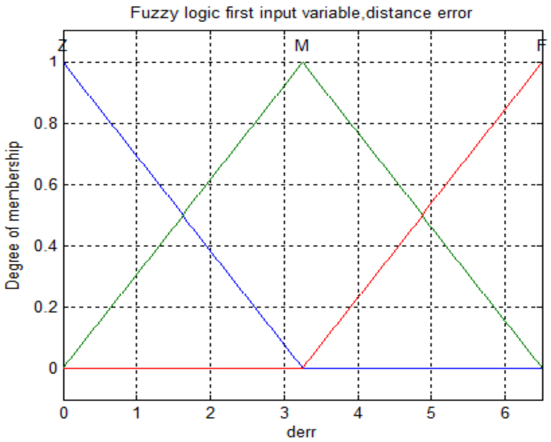

Fig. 8 Fuzzy membership functions for distance error

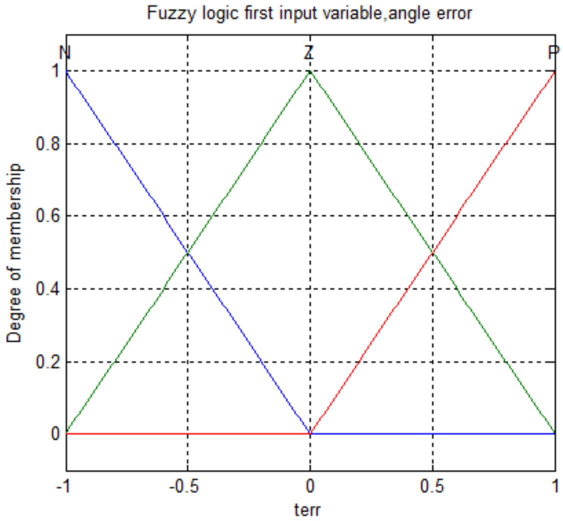

Fig. 9 Fuzzy membership functions for angle error

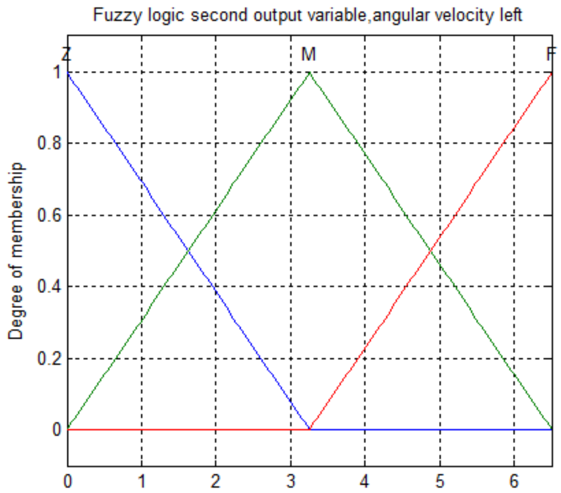

Fig. 10 Fuzzy membership function for angular velocity right

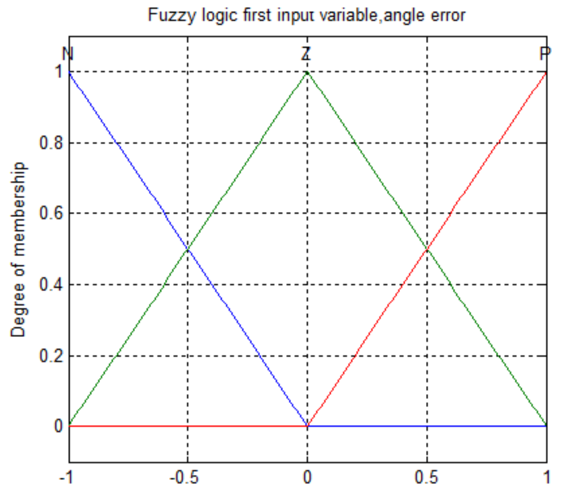

Fig. 11 Fuzzy membership function for angular velocity left

TABLE II
FUZZY RULES FOR VELOCITY OF THE RIGHT MOTOR

Δθ/ΔD	**F**	**M**	**Z**
N	M	M	S
Z	F	M	S
P	F	F	F

TABLE IIII
FUZZY RULES FOR VELOCITY OF THE LEFT MOTOR

Δθ/ΔD	**F**	**M**	**Z**
N	F	F	M
Z	F	M	S
P	M	M	S

The surface of the output variable as a function of the inputs is depicted in Figure 12 that shows the regularity of the change in the control signal [16].

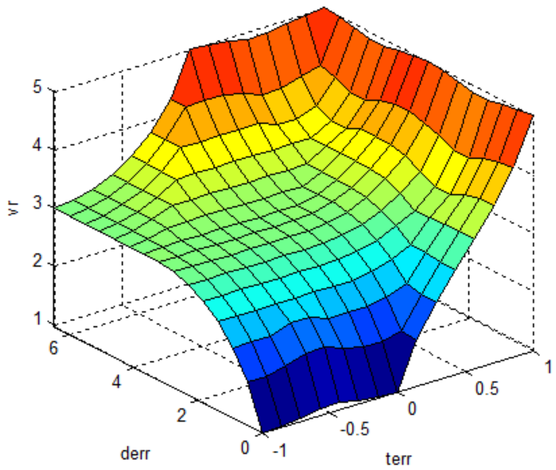

Fig. 12 Control based on angle error and distance error

The block diagram of mobile robot is shown in Figure 13

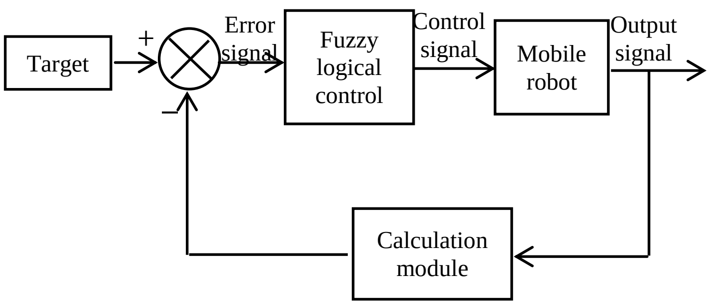

Fig. 13 Block diagramme of the mobile robot

In our case, we have chosen Mamdani Fuzzy Inference Systems with two inputs and two outputs.

The calculation module compares the actual robot coordinates with the coordinates of the target and computes the desired orientation θ_T and the angle error θ_{TR} between the actual current orientation θ and the desired orientation θ_T, are given by equations (3) (4), respectively

$$\theta_T = \tan^{-1}\left(\frac{Y_T - Y}{X_T - X}\right) \quad (3)$$

$$angle\ error = \theta_T - \theta \quad (4)$$

The distance of robot to the desired position or the target is expressed as:

$$D = \sqrt{(X_T - X)^2 + (Y_T - Y)^2}$$

We get error distance from following formula:

$$position\ error = D - distance$$

Where the vector $\begin{pmatrix} X \\ Y \\ \theta \end{pmatrix}$ represents the current position and orientation of the robot.

The vector $\begin{pmatrix} X_T \\ Y_T \\ \theta_T \end{pmatrix}$ represent the desired position and orientation of the robot.

The problem of controlling, with given a desired position, is reduced to get the distance and deviation angle equal to zero, to accomplish the goal of position control.

IV. SIMULATION AND RESULTS

The key of this application is the implementation of a controller based on fuzzy logic. The Figure 14 shows the simulink model of the mobile robot.

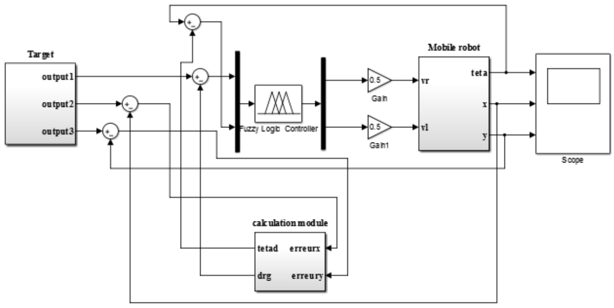

Fig. 14 Simulink model of the mobile robot

Recent research proved that Fuzzy logic controller with input membership of three has the best performance .

In order to verify the robustness of the proposed controller based on the least number of membership functions, different situations are chosen such as free space without and with disturbances. In the different cases, the robot task is to move from a given current position $(X = 0\ m, Y = 0\ m)$ to a desired goal position $(X = 20\ m, Y = 15\ m)$ in a free environment.

A. *First case: Continuous case and without perturbation*

The figure 15 shows that in simulation the robot moves from its initial position toward its final destination $(X_T = 20m, Y_T = 15m)$. The desired goal is achieved correctly. The results verify the effectiveness of the proposed controller.

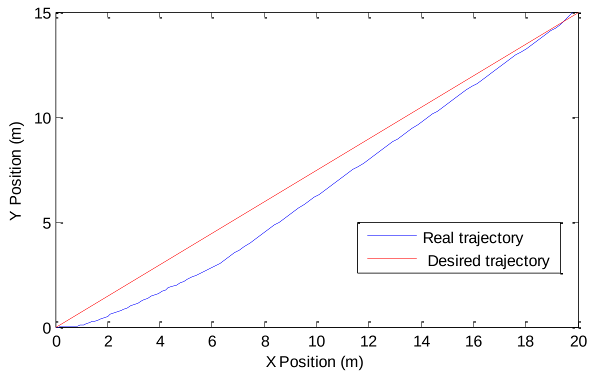

Fig. 15 Navigation of mobile robot without obstacles and distrbances

Figure 16 shows the evaluation and the limitation of the three coordinates which describe the mobile robot.

As depicted, the control variables are bounded so the proposed controller ensures system stability.

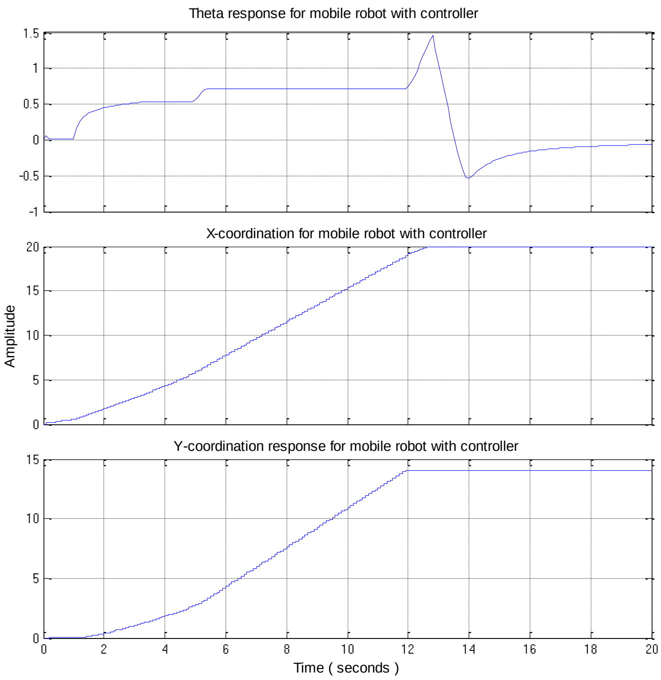

Fig. 16 The evaluation of three parameters without disturbances

The figure 17 shows the control variables as a function of time.

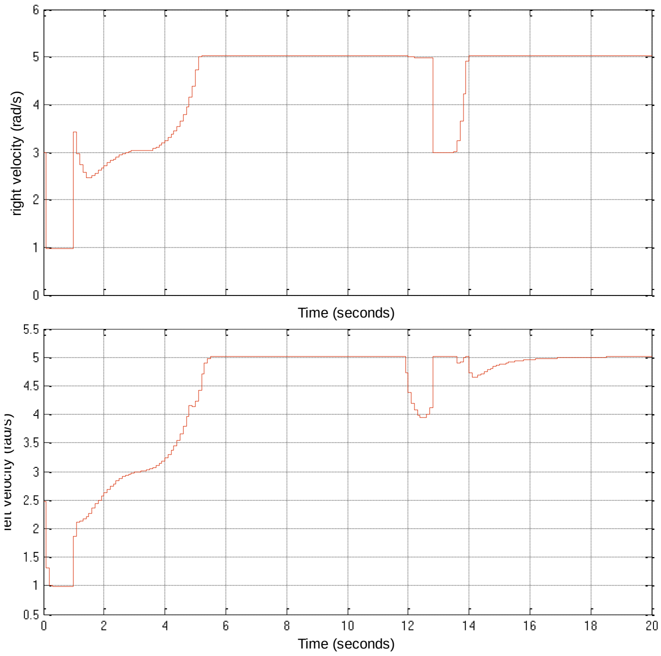

Fig. 17 The evaluation of control variables using Fuzzy Controller

As shown in Figure 17, the control variables (speed of left and right wheels) are progressed to reach the saturation then declined to zero.

Figure 18 shows the errors as a function of time.

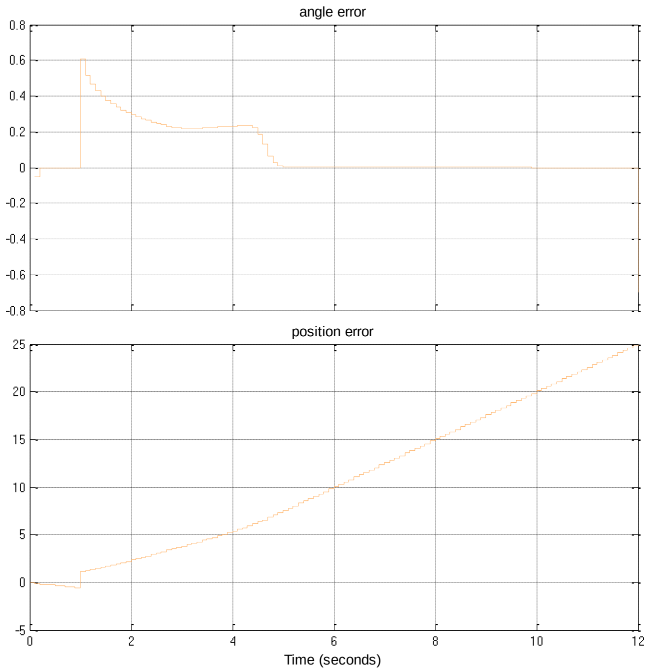

Fig. 18 The evaluation of control variables using Fuzzy Controller

B. Second case: continuous case with presence of disturbance

To confirm the relevance of the proposed control, it is proposed to simulate a mobile robot navigation to reach a target in presence of disturbance. The process and measurement noise are used the Simulink block diagram as white noise. The Simulink model with external disturbance is shown in Figure 19.

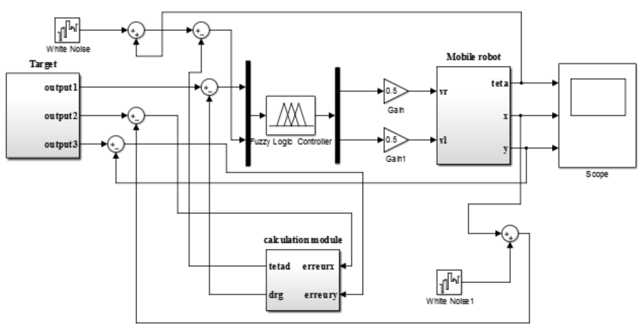

Fig 19 Simulink model of the robot with presence of disturbance

The simulation results in the presence of disturbances are given from Figure 20 to Figure 23.

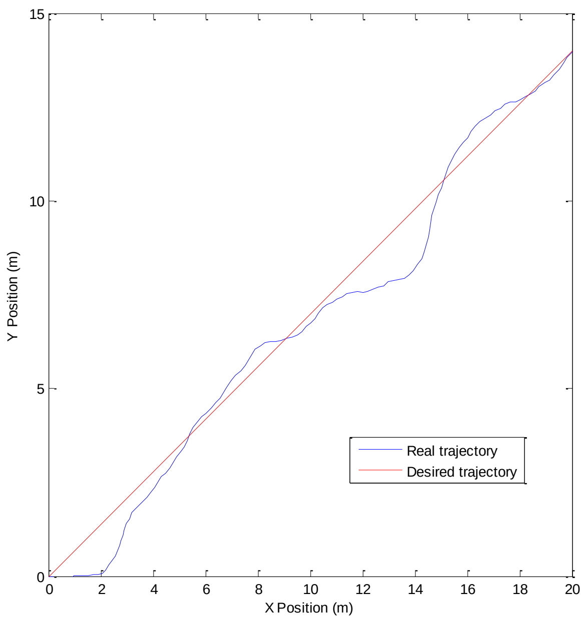

Fig. 20 Navigation of mobile robot in the presence of disturbances

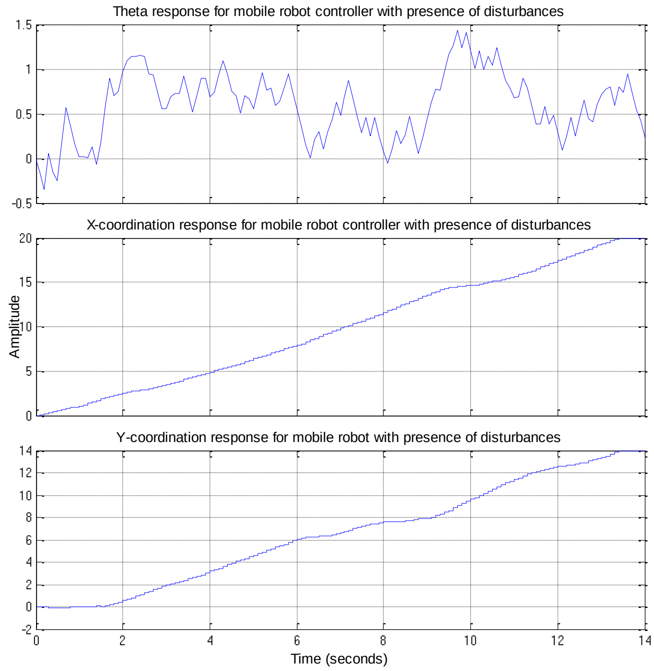

Fig. 22 The evaluation of three parameters in the presence of disturbances

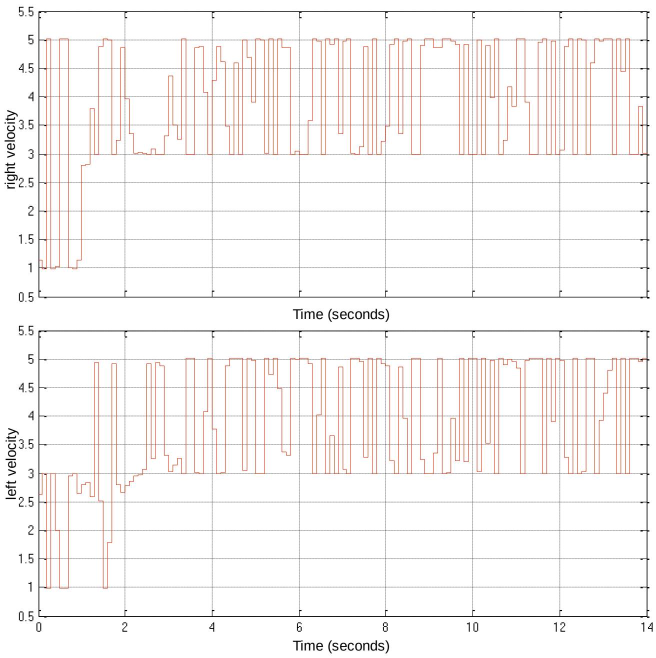

Fig. 21 The evaluation of control variables in the presence of disturbances

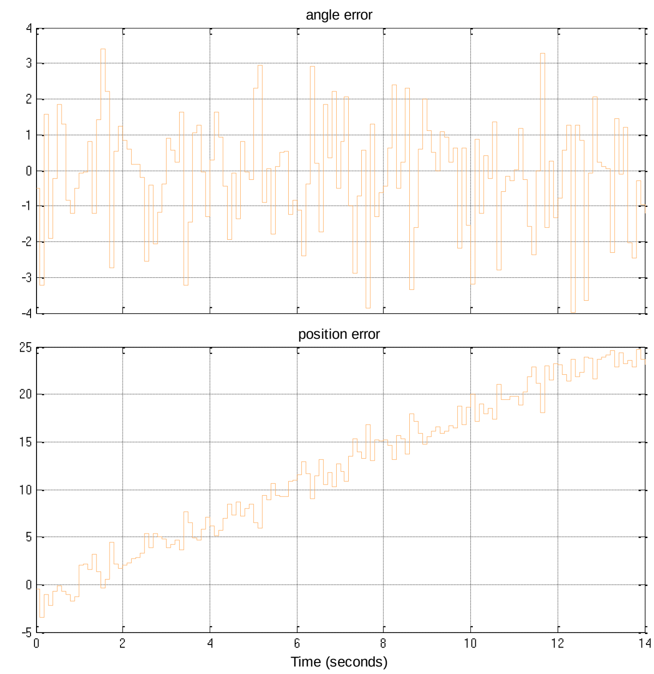

Fig. 23 Plots of error signals in the presence of disturbances

The plot in Figure 21 shows the velocities as a function of time.

As depicted, the robot is capable of reaching correctly its final destination.

Simulations show the effectiveness of the proposed controller for rejection of disturbances.

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V. Conclusions

In this paper, the problem of target trajectory tracking (a straight line) has been solved by using a fuzzy controller based on the least number of membership functions. The fuzzy logic rules were optimized for the best results. In this work, we have shown the proposed controller can be used in a successful and simple way of the autonomous navigation to deal with external disturbances. The results of our simulations present that proposed method is suitable to solve problem of target tracking. In all cases, the robot is able to move from its initial position to the goal. It has also been shown that the convergence and the boundedness of all signals in the system which assume the stability of the mobile robot. In future, the membership functions could be changed to have a more smooth control response.

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