Intelligent Control for a Perturbed Autonomous Wheeled Mobile Robot Using Type-2 Fuzzy Logic and Genetic Algorithms

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Abstract:

We describe a tracking controller for the dynamic model of a unicycle mobile robot by integrating a kinematic and a torque controller based on Type-2 Fuzzy Logic Theory and Genetic Algorithms. Computer simulations are presented confirming the performance of the tracking controller and its application to different navigation problems.

Keywords: *mobile robot, path planning, fuzzy logic, genetic algorithms, autonomous mobile robot navigation.*

1. Introduction

Mobile robots have attracted considerable interest in the robotics and control research community, because they have nonholonomic properties caused by nonintegrable differential constrains. The motion of nonholonomic mechanical systems [1] is constrained by its own kinematics, so the control laws are not derivable in a straightforward manner (Brockett condition [2]).

Furthermore, most reported designs rely on intelligent control approaches such as Fuzzy Logic Control (FLC) [17][19][22][23][24][25][26] and Neural Networks [27][28]. However the majority of the publications mentioned above, have concentrated on kinematics models of mobile robots, which are controlled by the velocity input, while less attention has been paid to the control problems of nonholonomic dynamic systems, where forces and torques are the true inputs: Bloch and Drakunov [1] and Chwa [29], used a sliding mode control to the tracking control problem.

This paper is organized as follows: Section II presents the problem statement and the kinematic and dynamic model of the unicycle mobile robot. Section III introduces the posture and velocity control design where a genetic algorithm is used to select the parameters of the posture controller. Robustness properties of the closed-loop system are achieved with a type-2 fuzzy logic velocity control system using a Takagi-Sugeno model where the wheel input torques, linear velocity, and angular velocity will be considered as linguistic variables. Section IV provides a simulation study of the unicycle mobile robot using the controller described in Section III. Finally, Section V presents the conclusions.

2. Problem statement

2.1 The Mobile Robot.

The model considered is a unicycle mobile robot (Figure 1), it consists of two driving wheels mounted of the same axis and a front free wheel.

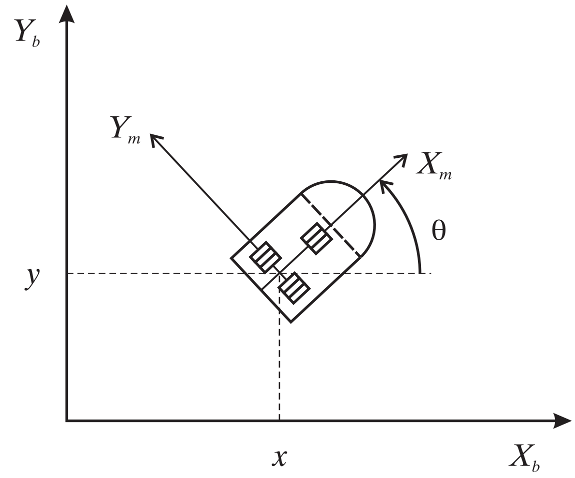


Fig. 1. Wheeled Mobile Robot.

A unicycle mobile robot is an autonomous, wheeled vehicle capable of performing missions in fixed or uncertain environments. The robot body is symmetrical around the perpendicular axis and the center of mass is at the geometric center of the body. It has two driving wheels that are fixed to the axis that passes through C and one passive wheel prevents the robot from tipping over as it moves on a plane. In what follows, it is assumed that the motion of the passive wheel can be ignored in the dynamics of the mobile robot represented by the following set of equations [5]:

$$M(q)\dot{\vartheta} + C(q,\dot{q})\dot{\vartheta} + D\vartheta = \tau + F_{ext}(t) \quad (1)$$

$$\dot{q} = \underbrace{\begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix}}_{J(q)} \underbrace{\begin{bmatrix} \nu \\ w \end{bmatrix}}_{\vartheta} \quad (2)$$

where $q = (x, y, \theta)^T$ is the vector of the configuration coordinates; $\vartheta = (\nu, w)^T$ is the vector of velocities; $\tau(\tau_1, \tau_2)$ is the vector of torques applied to the wheels of the robot where τ_1 and τ_2 denote the torques of the right and left wheel, respectively (Figure 1); $F_{ext} \in \mathbb{R}^2$ is the uniformly bounded disturbance vector; $M(q) \in \mathbb{R}^{2x2}$ is the positive-definite inertia matrix; $C(q,\dot{q})\vartheta$ is the vector of centripetal and coriolis forces; and $D \in \mathbb{R}^{2x2}$ is a diagonal positive-definite damping matrix. Equation (2) represents the kinematics of the system, where (x, y) is the position in the X - Y (world) reference frame; θ is the angle between the heading direction and the x-axis; ν and w are the linear and angular velocities, respectively.

Furthermore, the system (1)-(2) has the following non-holonomic constraint:

$$\dot{y}\cos\theta - \dot{x}\sin\theta = 0 \tag{3}$$

which corresponds to a no-slip wheel condition preventing the robot from moving sideways [6]. The system (2) fails to meet Brockett's necessary condition for feedback stabilization [2], which implies that no continuous static state-feedback controller exists that stabilizes the close-loop system around the equilibrium point.

The control objective is to design a fuzzy logic controller τ that ensures

$$lim_{t\to\infty} \| q_d(t) - q(t) \| = 0, \tag{4}$$

for any continuously, differentiable, bounded desired trajectory $q_d \in \mathbb{R}^3$ while attenuating external disturbances.

3. Fuzzy logic control design

This section illustrates the framework to achieve stabilization of a unicycle mobile robot around a desired path. The stabilizing control law for the system (1)-(2) can be designed using the backstepping approach [4] since the kinematics subsystem (2) is controlled indirectly through the velocity vector ν. The procedure to design the overall controller consists of two steps:

1) Design a virtual velocity vector $\vartheta_r = \vartheta$ such that the kinematic model (2) be uniformly asymptotically stable.

2) Design a velocity controller by using FLC that ensures.

$$\| \vartheta_r(t) - \vartheta(t) \| = 0, \qquad \forall t \geq t_s \tag{4}$$

where t_s is the reachability time.

In (5), it is considered that real mobile robots have actuated wheels, so the control input is τ that must be designed to stabilize the dynamics (1), without destabilizing the system (2), by forcing $\vartheta \in \mathbb{R}^2$ to reach the virtual velocity vector $\vartheta_r \in \mathbb{R}^2$ in finite-time. Roughly speaking, if (5) is satisfied asymptotically *(i, e;* $t_s = \infty$*)* then ϑ along $t < \infty$, consequently the mobile robot will be neither positioned nor oriented at desired point. Figure 2 illustrates the feedback connection which involves the fuzzy controller.

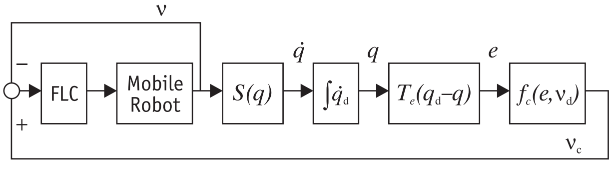


Fig. 2. Tracking control structure.

A. Posture Control Design

First, we focus on the kinematic model by designing a virtual control (ϑ_r) such that the control objective (4) is achieved. To this end, let us consider the reference trajectory $q_d(t)$ as a solution of the following differential equation:

$$\dot{q}_d = \begin{pmatrix} \cos\theta_d & 0 \\ \sin\theta_d & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_d \\ w_d \end{pmatrix} \tag{6}$$

where $\theta_d(t)$ is the desired orientation, and $\nu_d(t)$ and $w_d(t)$ denote the desired linear and angular velocities, respectively. In the robot's local frame, the error coordinates can be defined as

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \\ \tilde{q}_3 \end{pmatrix} = \underbrace{\begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{T_e(\theta)} \begin{pmatrix} x_d - x \\ y_d - y \\ \theta_d - \theta \end{pmatrix}, \tag{7}$$

where $(x_d(t), y_d(t))$ is the desired position in the world X - Y coordinate system, $\tilde{q}_1$ and $\tilde{q}_2$ are the coordinates of the position error vector, and $\tilde{q}_3$ is the orientation error. The associated tracking error model is

$$\begin{pmatrix} \dot{\tilde{q}}_1 \\ \dot{\tilde{q}}_2 \\ \dot{\tilde{q}}_3 \end{pmatrix} = \begin{pmatrix} w\tilde{q}_2 - \nu + \nu_d\cos\tilde{q}_3 \\ -w\tilde{q}_1 + \nu_d\sin\tilde{q}_3 \\ w_d - w \end{pmatrix}, \tag{8}$$

which is in terms of the corresponding real and desired velocities, is then obtained by differentiating (7) with respect to time.

In order to present the main result of this subsection, we need first to recall the following theorems [2].

Theorem 1 [12] (Uniform stability): Let $x = 0$ be an equilibrium point for $\dot{x} = f(x, t)$ and $D \subset \mathbb{R}^n$ be a domain containing $x = 0$. Let $V: [0, \infty] \times D \to \mathbb{R}^n$ be a continuously differentiable function such that

$$W_1(x) \leq V(x, t) \leq W_2(x) \tag{9}$$

$$\frac{\partial v}{\partial t} + \frac{\partial v}{\partial x} f(x, t) \leq 0 \tag{10}$$

for all $t \geq 0$ and for all $x \in D$, where $W_1(x)$ and $W_2(x)$ are continuous positive definite functions on D. Then, $x = 0$ is uniformly stable.

Theorem 2 [12] (Uniform asymptotic stability): Suppose the assumptions of Theorem 1 are satisfied with inequality (10) strengthened to

$$\frac{\partial v}{\partial t} + \frac{\partial v}{\partial x} f(x, t) \leq -W_3(x) \tag{11}$$

Theorem 3: Let the tracking error equations (8) be driven by the control law (virtual velocities)

$$\begin{aligned} \nu_r &= \nu_d\cos\tilde{q}_3 + \gamma_1\tilde{q}_1 \\ w_r &= w_d + \gamma_2\nu_d\tilde{q}_2 + \gamma_3\sin\tilde{q}_3 \end{aligned} \tag{12}$$

where γ_1, γ_2 and γ_3 are positive constants. If $\nu = \nu_r$ and $w = w_r$ for all $t \geq 0$ in (2), then the origin of the closed-loop system (8)-(12) is uniformly asymptotically stable.

Proof: Under the control (12), the closed-loop system takes the form:

$$\begin{pmatrix} \dot{\tilde{q}}_1 \\ \dot{\tilde{q}}_2 \\ \dot{\tilde{q}}_3 \end{pmatrix} = \begin{pmatrix} w_d\tilde{q}_2 + \gamma_2\nu_d\tilde{q}_2^2 + \gamma_3\tilde{q}_2\sin\tilde{q}_3 - \gamma_1\tilde{q}_1 \\ -w_d\tilde{q}_1 + \gamma_2\nu_d\tilde{q}_1\tilde{q}_2 - \gamma_3\tilde{q}_1\sin\tilde{q}_3 + \nu_d\sin\tilde{q}_3 \\ -\gamma_2\nu_d\tilde{q}_2 - \gamma_3\sin\tilde{q}_3 \end{pmatrix} \quad (13)$$

Note that the origin $(\tilde{q}_1, \tilde{q}_2, \tilde{q}_3)^T = 0$ is an equilibrium point of the closed-loop system but not unique because $\tilde{q}_3$ can adopt several postures *(i.e.,* $\tilde{q}_3 = 0, \pi, \ldots, n\pi$*)*. Genetic algorithms are applied for tuning the kinematic control gains γ_i, $i = 1, 2, 3$ to ensure that the error $\tilde{q} \in \mathbb{R}^3$ converges to the origin. The asymptotic stability theorem is invoked as a guideline to obtain bounds in the values of γ_i which shall guarantee convergence of the error $\tilde{q} \in \mathbb{R}^3$ to zero. For this purpose, let us introduce the Lyapunov function candidate

$$V(\tilde{q}) = \frac{1}{2}\tilde{q}_1^2 + \frac{1}{2}\tilde{q}_2^2 + \frac{1}{\gamma_2}(1 - \cos\tilde{q}_3) \quad (14)$$

which is positive definite. Taking the time derivative of $V(\tilde{q})$ along the solution of the closed-loop system (13), we get

$$\begin{aligned} \dot{V}(\tilde{q}) &= \tilde{q}_1\dot{\tilde{q}}_1 + \dot{q}_2\dot{\tilde{q}}_2 + \frac{1}{\gamma_2}\dot{\tilde{q}}_3\sin\tilde{q}_3 = \\ &= -\gamma_1\tilde{q}_1^2 - \frac{\gamma_3}{\gamma_2}(\sin\tilde{q}_3)^2 \leq 0 \end{aligned} \quad (15)$$

Thus concluding that for any positive constant γ_i, the closed-loop system is uniformly stable. To complete the proof it remains to note that $\tilde{q}_1, \tilde{q}_2, \tilde{q}_3 \in L_\infty^n; \tilde{q}_1, \tilde{q}_3 \in L_\infty^n$ and $\dot{\tilde{q}}_1, \dot{\tilde{q}}_2 \in L_\infty^n$ where

$$L_2^n = \left\{x(t): \mathbb{R}_+ \to \mathbb{R}^n \mid \|x(t)\|_2^2 = \int_0^\infty \|x(t)\|_2^2\, dt < \infty\right\}$$

$$L_2^n = \left\{x(t): \mathbb{R}_+ \to \mathbb{R}^n \mid \|x(t)\|_\infty^2 = \sup \|x(t)\|_2^2 < \infty\right\}$$

hence we conclude, by applying Barbalat's lemma that $\tilde{q}_1$ and $\tilde{q}_3$ converge to the origin. Finally, by invoking the Matrosov's Theorem [7], convergence of $\tilde{q}_2$ to the origin can be concluded.

The genetic algorithm was codified with a chromosome of 24 bits in total, eight bits for each of the gains. Figure 3 shows the binary chromosome representation of the individuals in the population. Different experiments were performed, changing the parameters of the genetic algorithm and the best results were obtained by comparing the corresponding simulations. Changing the crossover rate and the number of crossover points used did not affect the results. Also, changing the mutation rate did not affect the optimal results. The advantage of using the genetic algorithm to find the gains is that time-consuming manual search of these parameters was avoided.

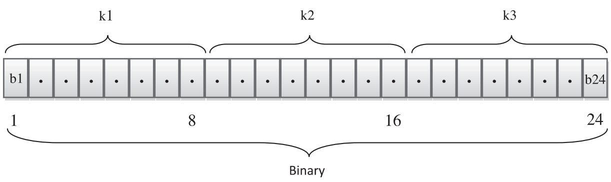


Fig. 3. Chromosome representation.

where bi, $i = 1, \ldots 24$ are binary values (0 or 1) representing the constants gains parameters.

B. Velocity Control Design

In this subsection a fuzzy logic controller is designed to force the real velocities of the mobile robot (1) and (2) to match those required in equations (12) of Theorem 3 to satisfy the control objective (4).

We design a Takagi-Sugeno fuzzy logic controller for the autonomous mobile robot, using linguistic variables in the input and mathematical functions in the output. The linear (ν_d) and the angular (w_d) velocity errors were taken as input variables and the right (τ_1) and left (τ_2) torques as the outputs. The membership functions used in the input are trapezoidal for the Negative (N) and Positive (P), and triangular for the Zero (C) linguistics terms. The interval used for this fuzzy controller is [-50 50]. Figure 4 shows the input variables and Figure 5 the output variables.

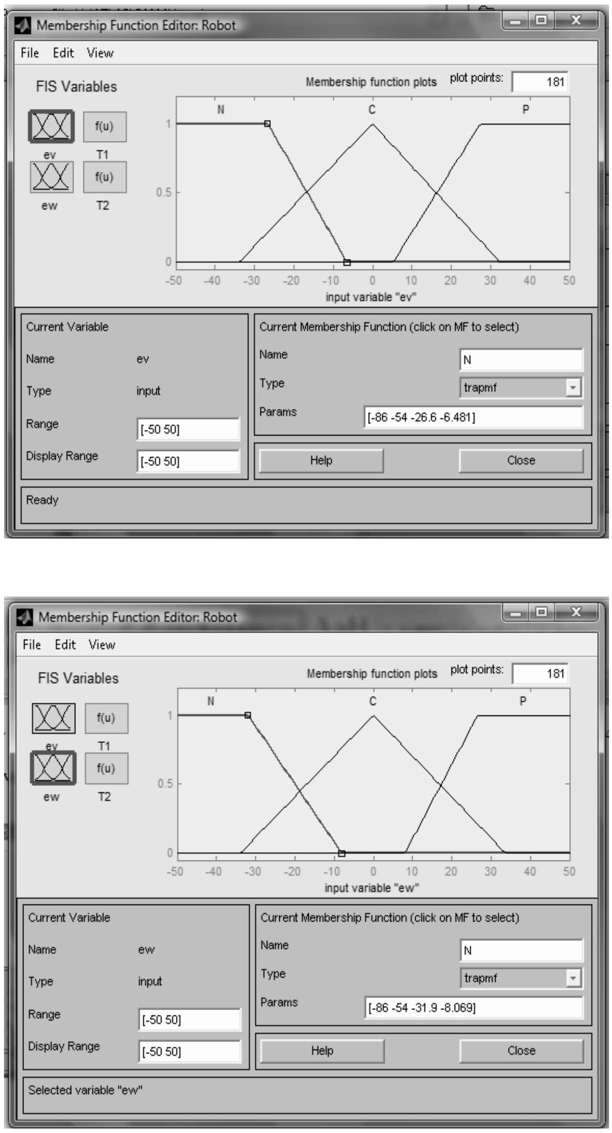


Fig. 4. (a) Linear velocity error. (b) Angular velocity error.

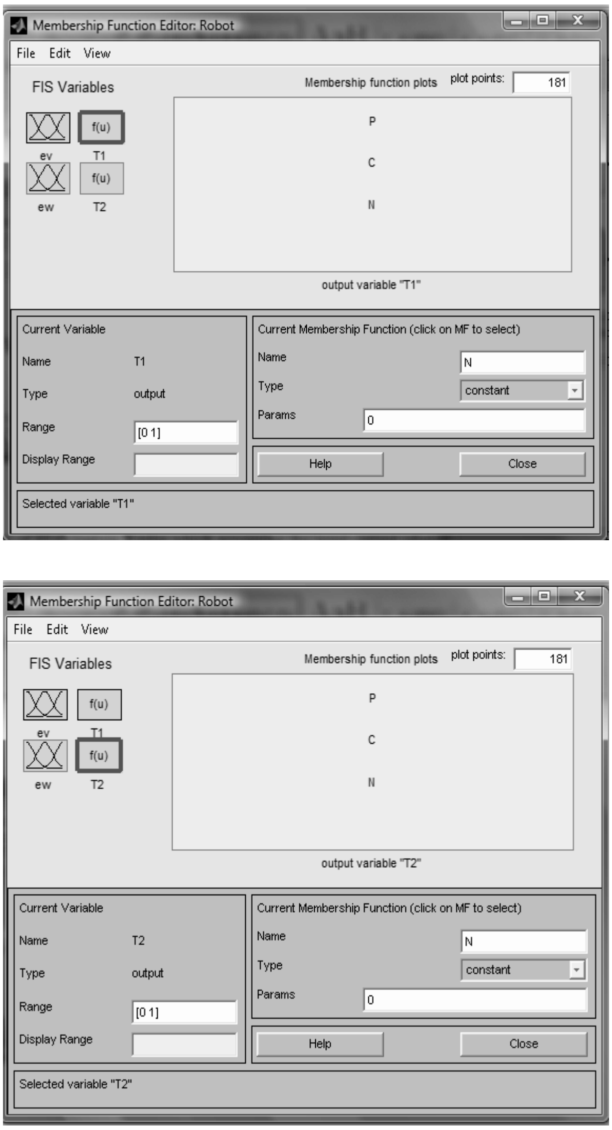


Fig. 5. (a) Right output (T1). (b) Left output (T2).

The rule set of the FLC contain 9 rules, which govern the input-output relationship of the FLC and this adopts the Takagi-Sugeno style inference engine [8], and we use a single point in the outputs (constant values), obtained using weighted average defuzzification procedure. In Table 1, we present the rule set whose format is established as follows:

Rule i: If e_v is G_1 and e_w is G_2 then F is G_3 and N is G_4

Where $G_1..G_4$ are the fuzzy set associated to each variable and $i = 1 \ldots 9$.

Table 1. Fuzzy rule set.

e_v / e_w	N	C	P
N	N/N	N/C	N/P
C	C/N	C/C	C/P
P	P/N	P/C	P/P

To find the best fuzzy controller, we used a the genetic algorithm to find the parameters of the membership functions. In figure 6 we show the chromosome with 28 bits (positions).

Inputs

- Linear velocity error
  - Negative, Zero, Positive
- Angular velocity error
  - Negative, Zero, Positive

Outputs

- Torque 1
  - Constant
    - Negative, Zero, Positive
- Torque 2
  - Constant
    - Negative, Zero, Positive

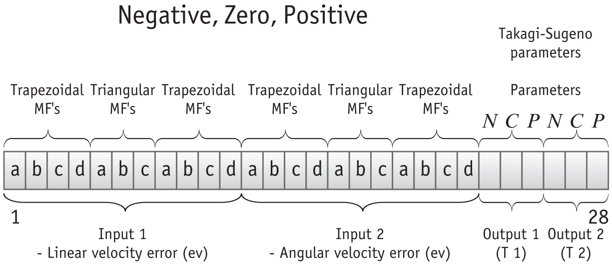


Fig. 6. Chromosome representation for the fuzzy logic controller.

Table 2. Parameters of the membership functions.

MF Type	Point	Minimum Value	Maximum Value
Trapezoidal	a	-50	-50
	b	-50	-50
	c	-15	-5.05
	d	-1.5	-0.5
Trapezoidal	a	-5	-1.75
	b	0	0
	c	1.75	5
Trapezoidal	a	0.5	1.5
	b	5.05	15
	c	50	50
	d	50	50

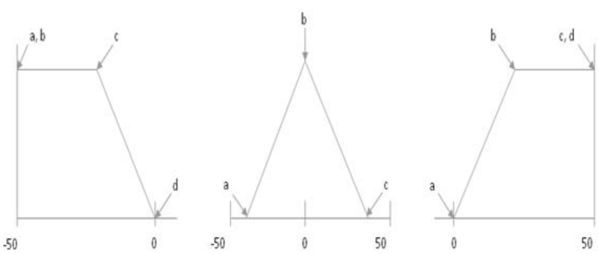


Fig. 7. Type of membership functions.

Table 2 shows the parameters of the membership functions, the minimal and the maximum values in the search range for the genetic algorithm to find the best fuzzy controller system and figure 7 shows the type of membership functions that we used.

4. Simulation results

In this section, we evaluate, through computer simulation performed in MATLAB® and SIMULINK®, the ability of the proposed controller to stabilize the unicycle mobile robot, defined by (1) and (2) where the matrix values

$$M(q) = \begin{bmatrix} 0.3749 & -0.0202 \\ -0.0202 & 0.3739 \end{bmatrix},$$

$$C(q,\dot{q}) = \begin{bmatrix} 0 & 0.1350\dot{\theta} \\ -0.1350\dot{\theta} & 0 \end{bmatrix},$$

and $D = \begin{bmatrix} 10 & 0 \\ 0 & 10 \end{bmatrix}$

were taken from [3].

The desired trajectory is the following one:

$$\vartheta_d(t) = \begin{cases} \nu_d(t) = 0.2(1 - exp(-t)) \\ w_d(t) = 0.4\sin(0.5\,t) \end{cases} \qquad (16)$$

and was chosen in terms of its corresponding desired linear ν_d and angular velocities w_d, subject to the initial conditions

$$q(0) = (0.1, 0.1, 0)^T \text{ and } \vartheta(0) = 0 \in \mathbb{R}^2$$

The gains γ_i , $i = 1,2,3$, of the kinematic model (12) were tuned by using genetic algorithm approach resulting in $\gamma_1 = 5$, $\gamma_2 = 24$ and $\gamma_3 = 3$ the best gains that were found.

4.1 Genetic algorithm results for the gains k1, k2 and k3.

To find these gains we changed the number of generations, the mutation and the crossover operators of the genetic algorithm represented in Table 3. Figure 8 shows the Simulink block diagram of the controller and Figure 9 shows the plot of the evolution of the population on the genetic algorithm finding the best gains.

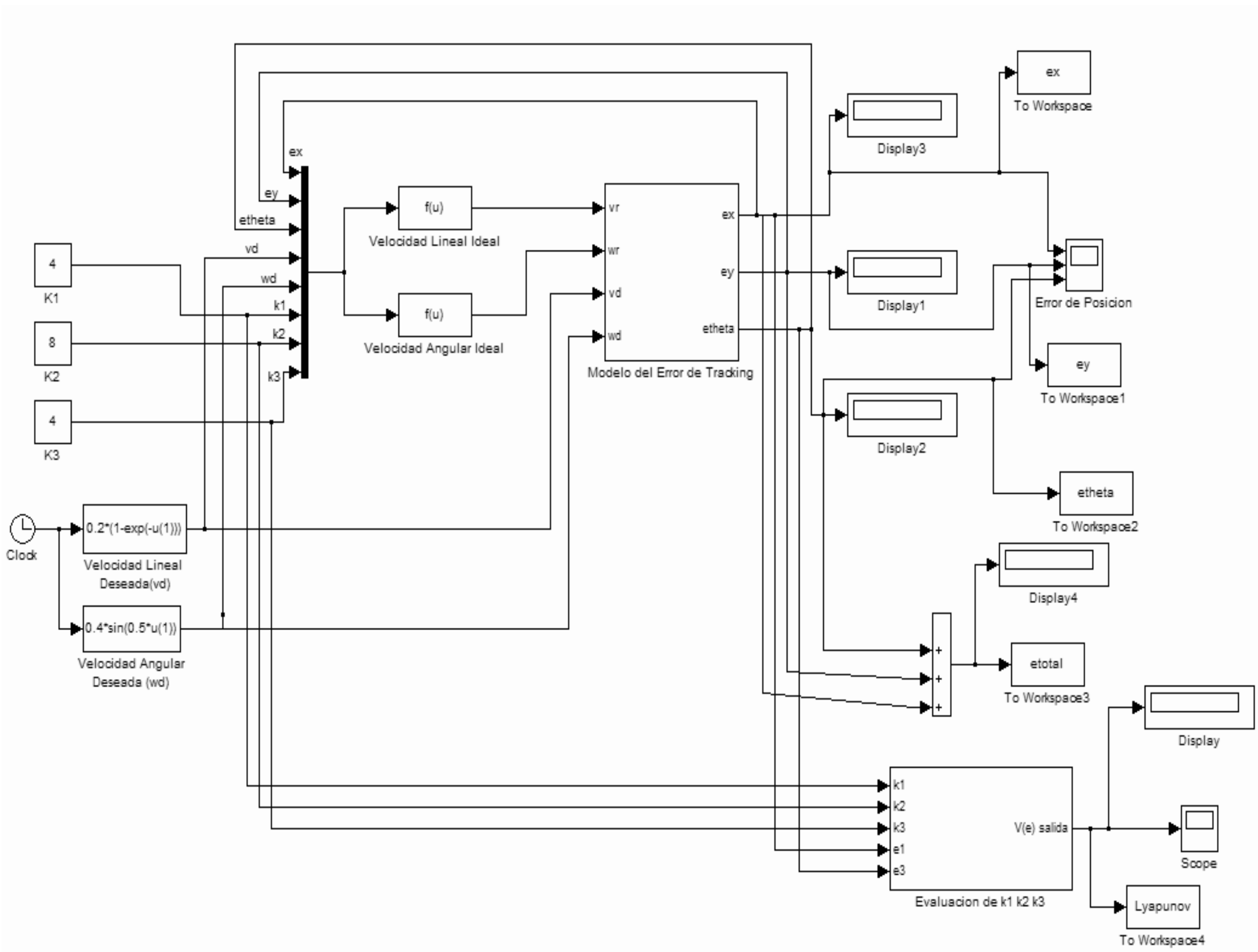


Fig. 8. Simulink block diagram.

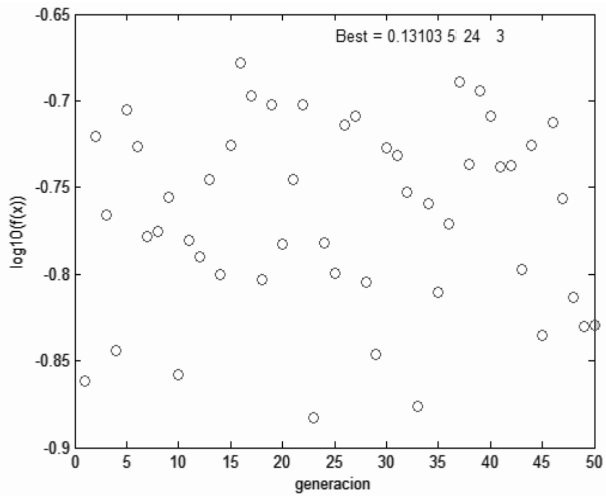


Fig. 9. Evolution of GA finding the optimal gains.

Table 3. Results of the simulation to find the constants k1, k2 and k3.

No.	Individuals	Generations	Crossover	Mutation	Average error	k1	k2	k3
1	100	70	0.8	0.3	14.1544	39	483	66
2	50	40	0.8	0.4	109.6417	451	416	80
3	20	15	0.7	0.4	41.4291	174	320	59
4	40	30	0.9	0.4	85.8849	354	311	51
5	60	80	0.9	0.4	116.6302	477	287	47
6	60	70	0.8	0.3	70.0033	293	382	59
7	70	100	0.7	0.2	31.4233	138	485	72
8	50	60	0.8	0.2	16.8501	74	402	59
9	40	20	0.5	0.2	101.0294	420	428	68
10	40	20	0.8	0.2	70.8432	299	481	78
11	55	25	0.8	0.3	15.0319	31	509	72
12	50	70	0.5	0.2	122.8667	507	406	65
13	30	50	0.8	0.3	103.7498	428	320	49
14	3	5	0.8	0.1	20.0183	27	507	98
15	2	10	0.8	0.1	31.4037	132	346	138
16	5	15	0.8	0.1	114.8469	477	219	27
17	30	50	0.8	0.1	4.1658	6	9	6
18	30	50	0.8	0.1	4.1844	6	9	5
19	30	50	0.8	0.1	4.0008	4	8	4
20	30	50	0.8	0.1	4.0293	4	5	4
21	50	40	0.8	0.4	3.8138	5	24	3
22	50	40	0.8	0.4	4.5141	10	16	6
23	50	40	0.8	0.4	6.9690	25	28	5
24	50	40	0.8	0.4	4.1202	6	15	5
25	70	80	0.8	0.3	3.9736	4	10	4
26	70	80	0.8	0.3	4.3726	7	10	4
27	30	20	0.8	0.1	4.0466	5	12	4
28	40	20	0.8	0.1	4.0621	5	11	4
29	70	80	0.8	0.3	4.7051	12	15	5
30	40	70	0.8	0.3	4.4199	8	11	5
21	40	70	0.8	0.3	4.0781	6	18	5
32	40	70	0.8	0.3	4.1669	6	11	5

Table 4. Best simulations results.

Average error	k1	k2	k3
3.8138	5	24	3

Figure 10 shows the plot of the best simulation results and Figure 11 shows an amplified plot.

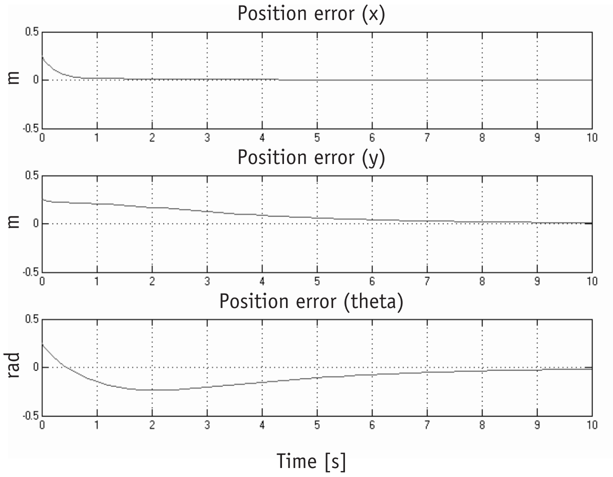


Fig. 10. Tracking errors.

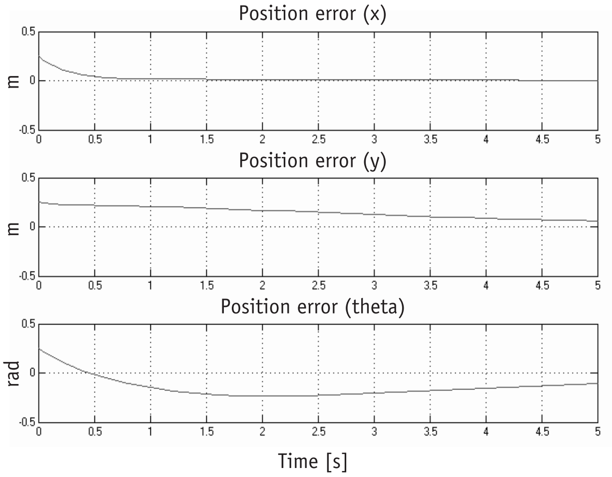


Fig. 11. Tracking errors amplified.

4.2 Genetic algorithms results for the optimization of the fuzzy logic controller (FLC).

Table 5 contains the results of the FLC, obtained by varying the values of generation number, percentage of replacement, mutation and crossover and Figure 12 shows the evolution of the GA.

Table 5. Genetic Algorithm results for FLC optimization.

No.	Individuals	Generations	%Replacement	Crossover	Mutation	Selection Method	Average error	G.A. time
1	50	30	0.7	0.7	0.2	Roulette	54.4800	7:18
2	100	25	0.7	0.8	0.3	Roulette	54.6818	12:11
3	20	15	0.7	0.8	0.2	Roulette	71.7411	1:26
4	10	20	0.7	0.8	0.2	Roulette	62.8466	1:21
5	80	25	0.7	0.7	0.4	Roulette	53.5221	9:57
6	150	50	0.7	0.6	0.3	Roulette	53.0742	43:15
7	90	60	0.7	0.9	0.4	Roulette	53.0466	44:43
8	10	25	0.7	0.8	0.2	Roulette	72.2374	2:09
9	65	40	0.7	0.8	0.2	Rolette	53.0663	22:52
10	30	25	0.7	0.9	0.5	Roulette	52.9952	6:21
11	70	50	0.7	0.8	0.3	Roulette	53.0325	29:17
12	80	50	0.7	0.9	0.3	Roulette	53.0354	33:32
13	200	100	0.7	0.4	0.1	Roulette	53.0092	2:43:28
14	15	10	0.7	0.8	0.5	Roulette	73.3989	1:14
15	15	25	0.7	0.9	0.2	Roulette	61.2800	3:03
16	30	40	0.7	0.7	0.2	Roulette	53.2949	10:28
17	50	60	0.7	0.6	0.4	Roulette	53.3909	1:05:14
18	20	50	0.7	0.6	0.2	Roulette	55.7303	9:13
19	80	20	0.7	0.8	0.6	Roulette	58.5557	13:13
20	100	80	0.7	0.8	0.3	Roulette	53.1265	6:16
21	30	60	0.7	0.8	0.5	Roulette	53.0742	14:43
22	25	40	0.7	0.8	0.6	Roulette	55.0232	8:10
23	70	60	0.7	0.8	0.4	Roulette	52.9960	34:44
24	35	40	0.7	0.7	0.3	Roulette	53.0621	11:30
25	45	50	0.7	0.7	0.3	Roulette	53.5664	18:19
26	60	40	0.9	0.8	0.5	Roulette	53.2134	20:38
27	80	50	0.9	0.4	0.1	Roulette	53.0627	33:37
28	40	30	0.9	0.9	0.4	Roulette	53.1393	10:07
29	100	35	0.9	0.7	0.4	Roulette	53.0731	29:01
30	80	45	0.9	0.7	0.2	Roulette	53.1208	29:50
31	5	20	0.9	0.9	0.2	Roulette	55.9529	0:49
32	10	15	0.9	0.8	0.2	Roulette	56.4612	1:16
33	15	15	0.9	0.7	0.4	Roulette	60.9834	2:01
34	15	40	0.9	0.8	0.2	Roulette	53.2684	5:12
35	5	30	0.9	0.9	0.3	Roulette	65.1652	1:19

No.	Individuals	Generations	%Replacement	Crossover	Mutation	Selection Method	Average error	G.A. time
36	10	15	0.9	0.8	0.1	Roulette	68.7056	1:55
37	20	25	0.9	0.6	0.2	Roulette	56.0865	4:49
38	16	80	0.9	0.6	0.2	Roulette	53.0621	11:31
39	10	35	0.9	0.7	0.5	Roulette	53.3866	3:08
40	14	20	0.9	0.8	0.6	Roulette	69.5199	3:15
41	6	30	0.9	1	0.4	Roulette	67.2005	1:31
42	12	60	0.9	0.8	0.3	Roulette	53.2353	6:04
43	26	30	0.9	0.6	0.3	Roulette	52.9617	6:40
44	10	15	0.9	0.6	0.3	Roulette	55.9491	1:20
45	6	50	0.9	0.9	0.5	Roulette	57.3704	1:38
46	6	12	0.9	0.9	0.4	Roulette	73.6621	0:37
47	11	15	0.9	0.5	0.2	Roulette	71.3523	1:26
48	8	20	0.9	0.8	0.3	Roulette	55.3165	1:27
49	22	18	0.9	0.7	0.6	Roulette	53.1705	3:19
50	15	12	0.9	0.8	0.9	Roulette	59.1193	1:30
51	30	14	0.9	0.6	0.6	Roulette	55.5028	3:32
52	60	18	0.9	0.5	0.5	Roulette	56.7301	9:07
53	90	24	0.9	0.8	0.7	Roulette	53.1139	18:16
54	120	70	0.9	0.5	0.4	Roulette	53.0621	1:04:26
55	28	17	0.9	0.5	0.5	Roulette	55.0976	2:39

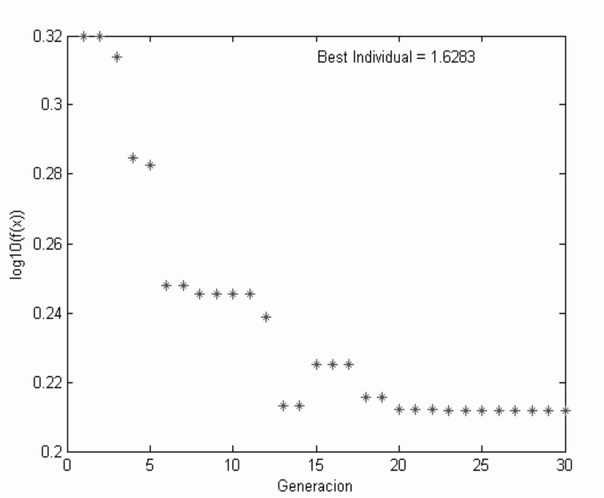
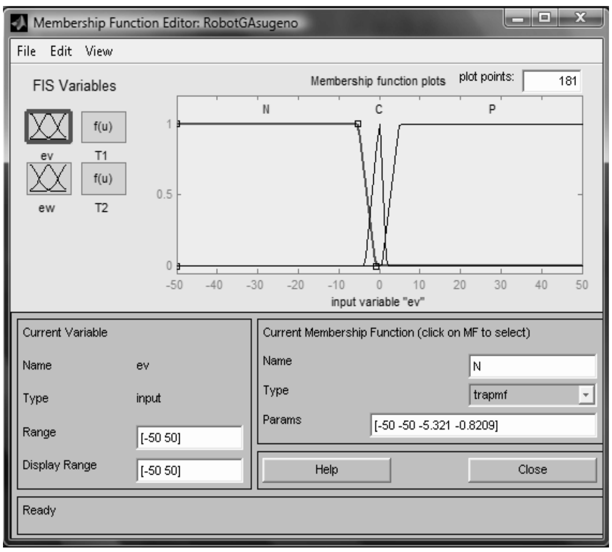


Fig. 12. Evolution of the GA for FLC optimization.



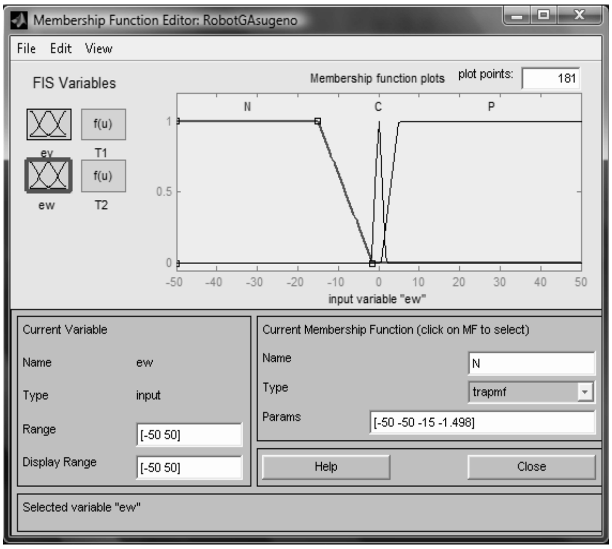


Fig. 13. (a) Linear velocity error, (b) Angular velocity error.

Continuing with the results, the best simulation for control of tracking is shown in Figure 13, which shows the parameters optimized by the genetic algorithm for the input variables (ev, ew). Figure 14 shows the block diagram used of the fuzzy logic controller that obtained the best simulations results.

Figure 15 shows the results of the linear and angular velocity errors, and Figure 16 shows the output results of the fuzzy controller, which is the torque applied to the wheels of the autonomous robot mobile.

The position errors of the autonomous robot mobile can be observed in Figure 17.

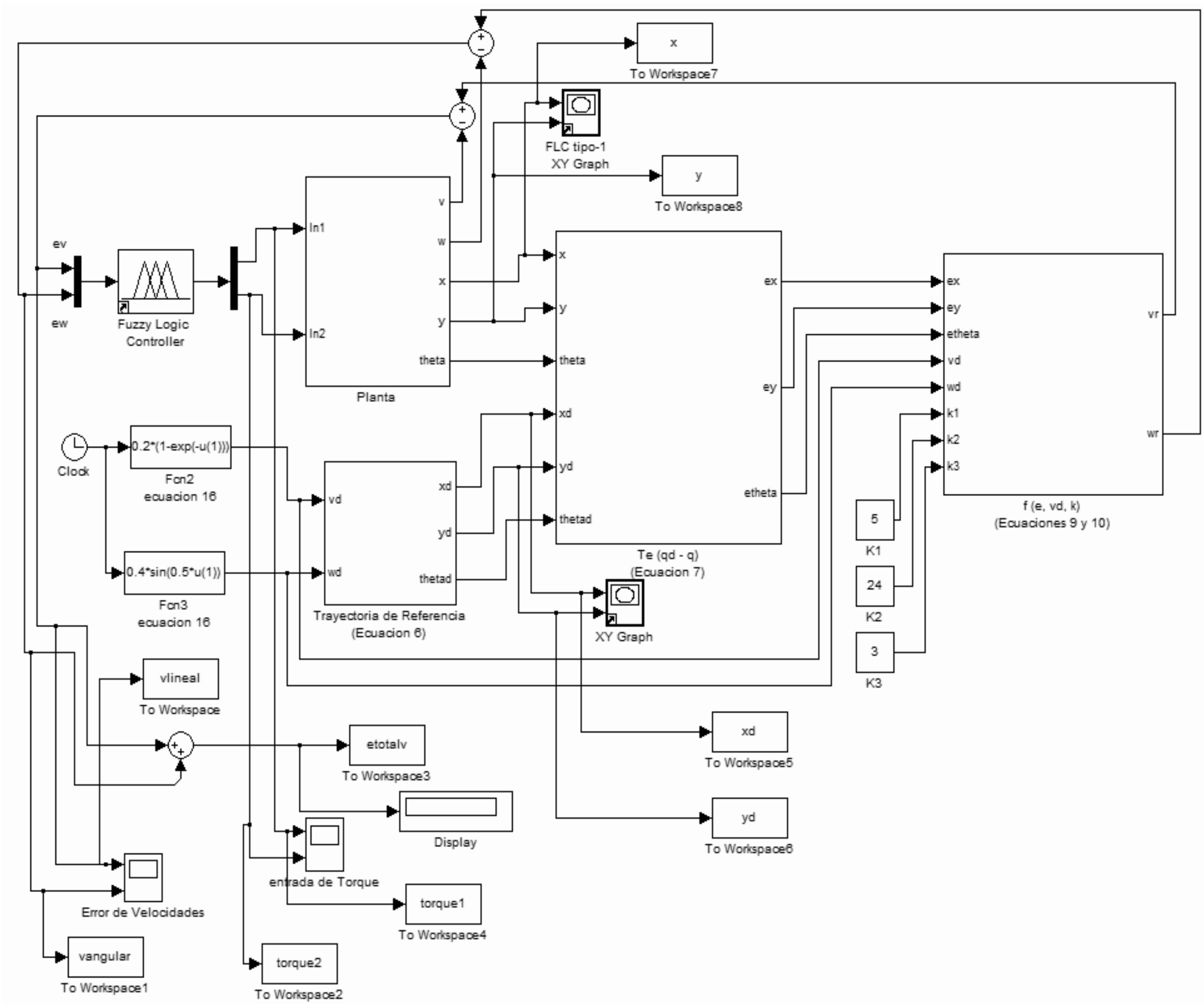


Fig. 14. Simulator block diagram for FLC.

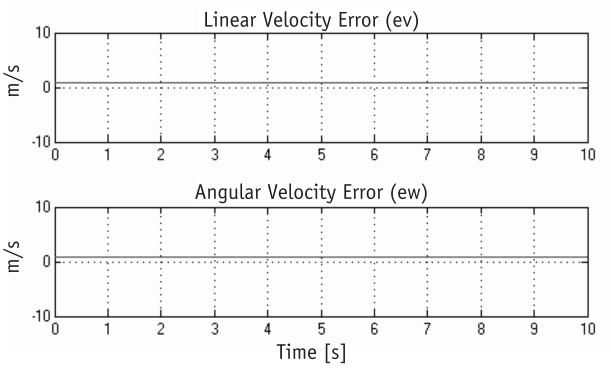


Fig. 15. Linear and angular velocity errors.

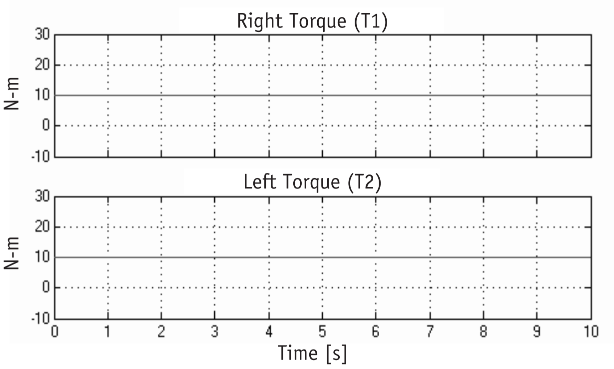


Fig. 16. Right and left torques.

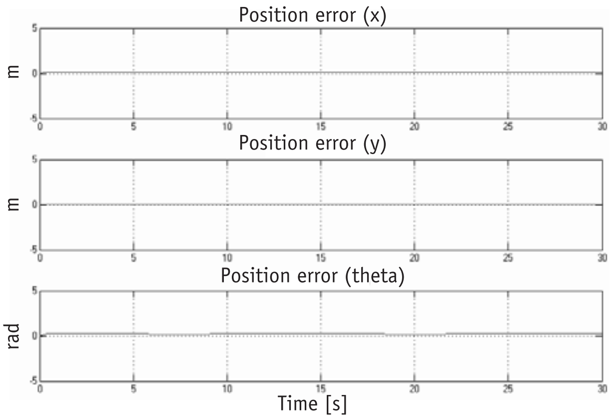


Fig. 17. Position errors in x, y, θ.

Figure 18 shows the desired trajectory and the obtained trajectory.

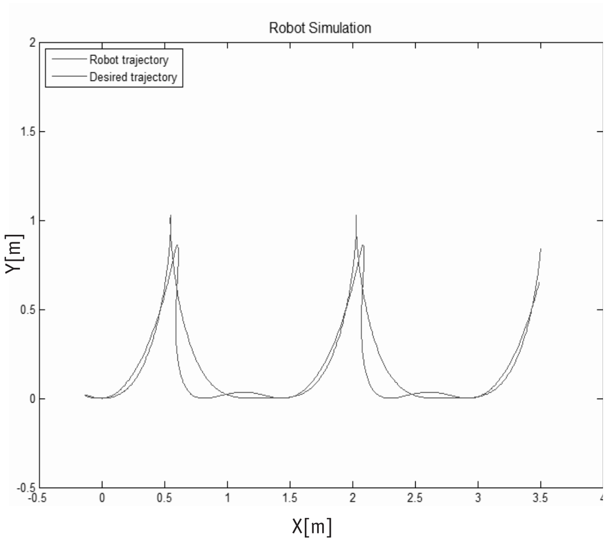


Fig. 18. Obtained trajectory.

5. Conclusions

We have designed a trajectory tracking controller taking into account the kinematics and the dynamics of the autonomous mobile robot.

Genetic algorithms are used for the optimization of the constants for the trajectory tracking and also for the optimization of the parameters of membership functions for fuzzy logic control.

Currently, the design of a type-2 fuzzy logic controller has been tested under a perturbed autonomous wheeled mobile robot, but more tests are in progress.

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