A Cognitive PID Neural Controller Design for Mobile Robot Based on Slice Genetic Algorithm

Dr. Ahmed Sabah Al-Araji
Control and Systems Engineering Department ,University of Technology/ Baghdad.
Email:dr.ahmed_alaraji@uotechnology.edu.iq

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ABSTRACT

The main core of this paper is to design a trajectory tracking control algorithm for mobile robot using a cognitive PID neural controller based slice genetic optimization in order to follow a pre-defined a continuous path. Slice Genetic Optimization Algorithm (SGOA) is used to tune the cognitive PID neural controller's parameters in order to find best velocities control actions of the right wheel and left wheel for the mobile robot. Pollywog wavelet activation function is used in the structure of the cognitive PID neural controller. Simulation results and experimental work show the effectiveness of the proposed cognitive PID neural tuning control algorithm; This is demonstrated by the minimized tracking error and the smoothness of the velocity control signal obtained, especially with regards to the external disturbance attenuation problem.

Keywords: Slice Genetic Algorithm; Cognitive PID Controller, Mobile Robots; Trajectory Tracking.

تصميم مسيطر عصبي تناسبي تكاملي تفاضلي مدرك لإنسان آلي متنقل مبني على أساس خوارزمية الشرائح الجينية

الخلاصة

أن المحور الرئيسي لهذا البحث هو تصميم خوارزمية مسيطر تتابع مسار لإنسان آلي متنقل باستخدام مسيطر عصبي تناسبي تكاملي تفاضلي أساسه أمثلية الشرائح الجينية لكي يتبع مسار مستمر معرف مسبقا.
لقد تم استخدام خوارزمية الشرائح الجينية لتنغيم عناصر المسيطر العصبي التناسبي التكاملي التفاضلي المدرك لكي يجد أفضل أشارة سرعة للإنسان الآلي المتحرك. أن الدالة الفعالة التي استخدمت في هيكلية المسيطر العصبي التناسبي التكاملي التفاضلي المدرك هي (Pollywog wavelet).
من خلال نتائج المحاكاة والأعمال التجريبية, أن فعالية خوارزمية تنغيم المسيطر المقترح تقوم بتقليل الخطأ ألتتابعي لمسار الإنسان الآلي المتحرك مع توليد أشارة سرعة ناعمة, برغم من وجود التأثير الاضطرابي الخارجي.

INTRODUCTION

In the last decade, there has been an increasing amount of research on the subject of wheel-based mobile robots which have attracted considerable attention in various industrial and service applications. For example, room cleaning, lawn mowers, factory automation, transportation, nuclear-waste cleaning, etc [1].

These applications require mobile robots to have the ability to track specified path stability; therefore, several studies have been published for solving the mobile robot path tracking control problems which can be classified into three categories: The first category is the position estimation control approach for navigation problems of the mobile robot on interactive motion planning in dynamics environments and obstacle motion estimation [2]. The second category for navigation problems of the mobile robot is path planning and execution. The path planning is generated based on a prior map of the environment while the executed path is planned using certain optimization algorithms based on a minimal time, minimal distance or minimal energy performance index. Many methods have been developed for avoiding both static and moving obstacles as presented in [3]. The third category for the navigation problems of mobile robot is designing and implementing the driving control that the mobile robot must track to follow a desired path accurately and minimize the tracking error.

Tracking errors of mobile robot causes collisions with obstacles due to deviations from the planned path and also causes the robot to fail to accomplish the mission successfully. It also causes an increase of the traveling time, as well as the travel distance, due to the additional adjustments needed to satisfy the driving sates. The major reasons for tracking error for mobile robot are the small rotation radius or not constant on the path such as the complex curvature or randomly curvature [4].

The traditional control methods for trajectory tracking the mobile robot have used linear or non-linear feedback control while artificial intelligent controller were carried out using neural networks or fuzzy inference [5].

There are other techniques for trajectory tracking controllers such as predictive control technique. Predictive approaches to path tracking seem to be very promising because the reference trajectory is known beforehand. Model predictive trajectory tracking control was applied to a mobile robot where linearized tracking error dynamics was used to predict future system behaviour and a control law was derived from a quadratic cost function penalizing the system trucking error and the control effort [6].

In addition, an adaptive trajectory-tracking controller based on the robot dynamics was proposed in [7]. Intelligent control architecture for two autonomously driven wheeled robot was developed in [8] that consists of the fuzzy inference as main controller and the neural network is an auxiliary part.

The fundamental essence of the contribution of this work can be understood considering the following points.

- Modify and improve the genetic algorithm through the proposed slice genetic algorithm that has a novel modified with high efficiency algorithm in terms of reducing the number of function evaluation through minimizing the population size and the number of iteration.
- The analytically derived tuning control law which has significantly high computational accuracy to find the optimal parameters for the cognitive PID controller in order to obtain the best control action and lead to minimizing tracking error of the mobile robot based on the proposed slice genetic optimization algorithm.

- Investigation of the controller robustness performance through adding boundary unknown disturbances.

The remainder of the paper is organized as follows: section two is a description of the kinematics model of the non-holonomic wheeled mobile robot. In section three, the proposed cognitive PID neural controller is derived based on slice genetic algorithm. The simulation results and experimental work of the proposed controller are presented in section four and the conclusions are drawn in section five.

Nonholonomic Wheeled Mobile Robot Model

In this study, the nonholonomic wheeled mobile robot is considered as having two degrees of mobility and zero degree of steering ability. Thus, the model consists of two wheels mounted on the same axis and one castor wheel as an omni directional in the back of robot platform to make the mobile robot more stable, as shown in Fig. 1 [9].

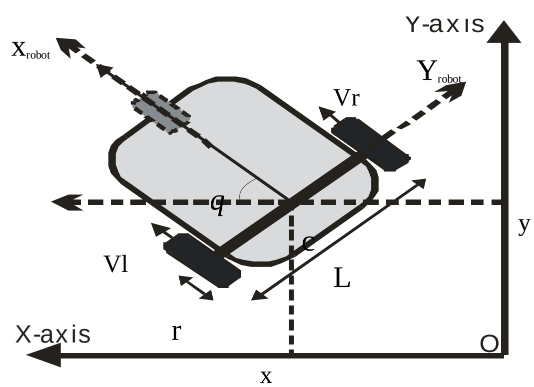


Figure (1). Mobile robot

The radius of any wheel is , the distance between the two wheels is and the center of mobile robot mass is .

In the global coordinate frame, the pose vector of the mobile robot is defined by equation (1):

$$q = (x, y, q)^T \qquad \ldots(1)$$

x and y which are located in the middle axis of the mobile robot wheels represent the coordinate of the center point while q is the robotic orientation angle measured with respect to the X-axis.

The kinematic equations of the mobile robot in the world frame can be represented by equations (2,3,4) which are based on a pure rolling and non slipping condition, which is referred as the non-holonomic constraint [10 and 11], as shown in equation (5):

$$\dot{x}(t) = V_I(t)\cos(q(t)) \qquad \ldots(2)$$

$$\dot{y}(t) = V_I(t)\sin(q(t)) \qquad \ldots(3)$$

$$\dot{q}(t) = V_w(t) \qquad \ldots(4)$$

Where

Vl and Vw, are the linear and angular velocities.

$$-\dot{x}(t)\sin q(t) + \dot{y}(t)\cos q(t) = 0 \qquad \ldots(5)$$

In the discrete-time domain, the current form of the pose equations as follows [12]:

$$q(k) = \frac{[V_R(k) - V_L(k)]}{L} Ts + q(k-1) \qquad \ldots(6)$$

$$x(k) = \frac{[V_R(k) + V_L(k)]}{2} \cos(q(k))T_s + x(k-1) \qquad \ldots(7)$$

$$y(k) = \frac{[V_R(k) + V_L(k)]}{2} \sin(q(k))T_s + y(k-1) \qquad \ldots(8)$$

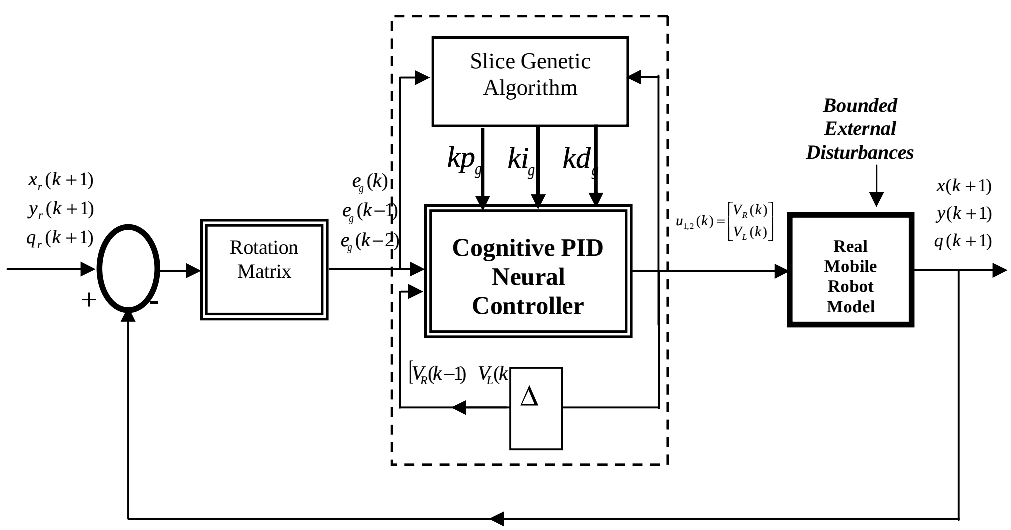
where

$x(k), y(k), q(k)$ are components of the pose at the k step movement.

T_s is the sampling time.

Trajectory Tracking Control Design

The proposed structure of the trajectory tracking control algorithm for mobile robot can be given in the form of block diagram, as shown in Fig. 2.



Δ is defined as a delay mapping.

Figure(2). Trajectory tracking controller for mobile robot.

The structure of the proposed controller consists of two parts:

a) Cognitive PID neural controller.

b) Slice genetic algorithm.

Cognitive PID Neural Controller

The cognitive PID neural controller is very important because it is necessary to stabilize the tracking error of the system by generating best velocity control signal that will minimize the tracking error of the mobile robot when the output of the mobile robot drift from the desired point in the presence of external disturbance. The proposed cognitive PID neural controller for MIMO mobile robot system can be shown in Fig. 3.

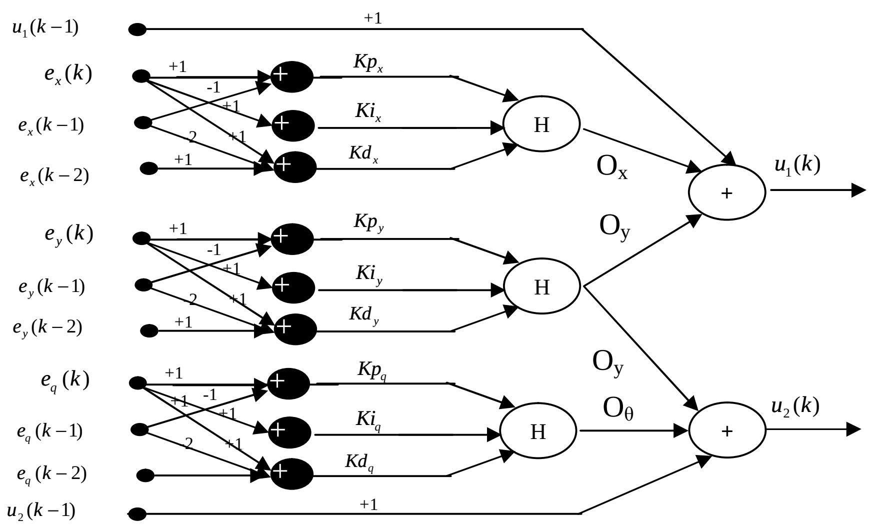


Figure (3). The cognitive PID neural controller structure.

It has the characteristics of control agility, strong adaptability, good dynamic characteristic and robustness because it is based on that of a conventional PID controller that consists of three terms: proportional, integral and derivative where the standard form of a PID controller is given in the s-domain as equation (9) [13].

$$Gc(s) = P + I + D = K_p + \frac{K_i}{s} + K_d s \qquad \ldots(9)$$

where

K_p, K_i and K_d are called the proportional gain, the integral gain and the derivative gain respectively.

The proposed cognitive PID neural controller scheme is based on the discrete-time PID as equation (10) [14].

$$u_{1,2}(k) = u_{1,2}(k-1) + Kp_g[e_g(k) - e_g(k-1)] + Ki_g e_g(k) + Kd_g[e_g(k) - 2e_g(k-1) + e_g(k-2)] \ldots(10)$$

Where

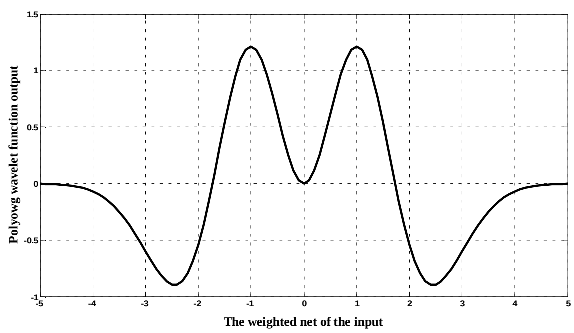
$g = x, y, q$.

Therefore, the tuning PID input vector consists of $e_g(k)$, $e_g(k-1)$, $e_g(k-2)$ and $u_{1,2}(k-1)$, where $e_g(k)$ and $u_{1,2}(k-1)$ denote the input error signals and the PID output signal respectively. The proposed control law of the feedback right and left velocity (u_1 and u_2) respectively can be proposed as follows:

$$u_1(k) = u_1(k-1) + o_x + o_y \quad \ldots(11)$$

$$u_2(k) = u_2(k-1) + o_q + o_y \quad \ldots(12)$$

o_x, o_y and o_q are the outputs of the neural networks that can be obtained from non-linear Polywog wavelet activation functions [15], as shown in Fig. 4 and has nonlinear relationship as presented in the following function:



Figure(4). Polywog wavelet function.

$$o_g = (3(net_g)^2 - (net_g)^4)e^{-0.5(net_g)^2} \quad \ldots(13)$$

net_g is calculated from this equation:

$$net_g(k) = Kp_g[e_g(k) - e_g(k-1)] + Ki_g e_g(k) + Kd_g[e_g(k) - 2e_g(k-1) + e_g(k-2)] \quad \ldots(14)$$

The control parameters Kp_g, Ki_g and Kd_g of the cognitive PID neural controller are adjusted using slice genetic optimization algorithm. In the local coordinates with respect to the body of the mobile robot, the configuration error $q_e = [x_e, y_e, q_e]^T$ can be presented by $q_e = R_o(q_r - q)$:

$$\begin{bmatrix} x_e \\ y_e \\ q_e \end{bmatrix} = \begin{bmatrix} \cos q & \sin q & 0 \\ -\sin q & \cos q & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x \\ y_r - y \\ q_r - q \end{bmatrix} \quad \ldots(15)$$

Where

R_o is the transformation matrix.

Learning Slice Genetic Algorithm (SGA)

Genetic algorithm is an intelligent optimization technique that relies on the parallelism found in nature; in particular its searching procedures are based on the mechanics of natural selection and genetics [16]. GAs is used regularly to solve difficult search, optimization, and machine-learning problems that have previously resisted automated solutions.

They can be used to solve difficult problems quickly and reliably. These algorithms are easy to interface with existing simulations and models, and they are easy to hybridize. GAs includes three major operators: selection, crossover, and mutation, in addition to four control parameters: population size, selection pressure, mutation rate and crossover [16].

In this work, it is hoped to improve the coverage characteristics and response accuracy by reducing the processing time and the tracking error for the mobile robot system thus, the SGA is employed to tune the control gain parameters (k_x, k_y, k_q) of the cognitive PID neural controller. The SGA is an improved form of the classic GA, it has same evolutionary operators, i.e., crossover and mutation which are the most important parts responsible for the performance influencing. The main cores of SGA are dividing the population into slices and duplicating good individuals. The operation of dividing leads to implementing the optimization in multi dimensions this will speed up the process of optimization while the process of duplication will give high opportunity to good individuals to exhibit all the best traits especially when applying random crossover to it [16].

The cognitive PID neural controller has nine parameters (k_x, k_y, k_q) to be optimized by the SGA and any number of slices >1 may satisfy. In this work, it is satisfactory to take four slices, as shown in Fig. 5.

The mean square error function is proposed as a criterion for estimating the model performance for multi-input multi-output (MIMO) mobile robot system, as in equation. (16):

$$J = \frac{1}{N}\sum_{k=1}^{N}[(e_x)^2 + (e_y)^2 + (e_q)^2 + (VR_{ref} - VR)^2 + (VL_{ref} - VL)^2] \qquad \ldots(16)$$

Since the SGA maximizes its fitness function, it is necessary to map the objective function (MSE) to the fitness function by using equation. (17) [17].

$$fitness = \frac{1}{objectivefunction + m} \qquad \ldots(17)$$

Where

the m is a constant > 0 chosen to avoid division by zero.

The tuning steps of the cognitive PID neural controller parameters by using SGA can be described in detail as follows:

Step 1: Initialize randomly 4 slices with dimension 8 ×9, i.e. population size (number of individuals) equals to 72.

Step 2: Calculate the fitness of each individual in each slice.

Step 3: For each slice vertically find the global maximum fitness by using equation (17).

Step 4: Horizontally find the optimal solution for all slices “the first slices optimal individual is got now.

Step 5: Duplicate the individual horizontally, which sponsors with horizontal maximum fitness.
Step 6: Make a selection as in Classic GA
Step 7: Apply arithmetic random crossover with crossover probability 0.85 (this will let the duplicated individuals produce their best).
Step 8: Apply mutation as in Classic GA with mutation probability of 0.01.
Step 9: Calculate the fitness vertically then find the slices for global maximum fitness.
Step 10: Horizontally find the optimal solution for all slices.
Step 11: Find the optimal global by comparing step 11 to step 4.
Step 12: Compare individual's fitness in the current generation, with the previous one, and then pick out the best individuals to create the new population.
Step 13: Repeat Steps (6 to 12) until the stopping criterion is satisfied**.**

Figure(5). The slice genetic population.

SIMULATION RESULTS AND EXPERIMENTAL WORK

The kinematic model of the non-holonomic mobile robot described in section 2 is used and the proposed controller was verified by means of computer simulation using MATLAB package. The parameter values of the robot model are taken from [18]: L=0.45 m, r=0.076 m and sampling time is equal to 0.5 second. The proposed cognitive PID neural controller scheme as in Fig. 3 is applied to model of mobile robot and it used the proposed learning algorithm steps of slice genetic algorithm for tuning the controller parameters. The first stage of operation is to set the following parameters of the SG algorithm:

Slice number is equal to 4. Population size is equal to 18 in each slice. Number of iteration is equal to 20. Number of weight in each slice is 9 because there are nine parameters of cognitive PID neural controller.

The simulation is carried out by tracking a desired position (x, y) and orientation angle (q) with continuous trajectory in the tracking control of the mobile robot where the desired path which has explicitly continuous gradient with rotation radius changes, this trajectory can be described by the following:

$$x_r(t) = -2.5 \times \sin(\frac{2pt}{30}) \qquad \ldots(18)$$

$$y_r(t) = 2.5 \times \sin(\frac{2pt}{20}) \qquad \ldots(19)$$

$$q_r(t) = 2\tan^{-1}\left(\frac{\Delta y_r(t)}{\sqrt{(\Delta x_r(t))^2 - (\Delta y_r(t))^2} + \Delta x_r(t)}\right) \qquad \ldots(20)$$

The mobile robot model starts from the initial posture $q(0) = [-0.5, 0, 0]$ as its initial conditions. A disturbance term $[0.01\sin(2t) \quad 0.01\sin(2t)]^T$ [9] is added to the mobile robot system as unmodelled kinematics disturbances in order to prove the adaptation and robustness ability of the proposed controller. The mobile robot trajectory tracking is obtained by the proposed controller, as shown in Fig. 6. These figures demonstrate excellent position and orientation tracking performance in spite of the existence of bounded disturbances.

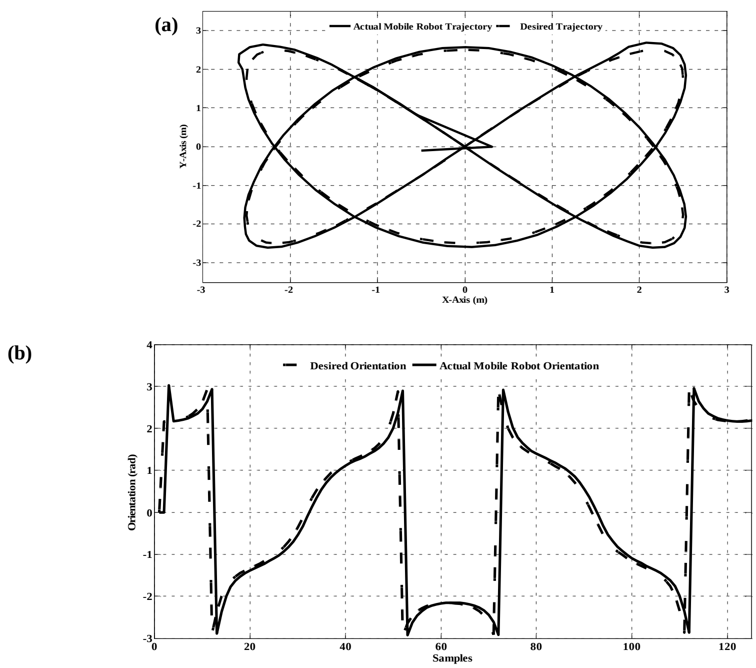


Figure (6). Simulation results (a) desired trajectory and actual mobile robot trajectory; (b) desired orientation and actual mobile robot orientation.

The adaptive learning and robustness of cognitive PID neural controller show small effect of these disturbances. The simulation results demonstrated the effectiveness of the proposed controller by showing its ability to generate small smooth values of the control input velocities for right and left wheels without sharp spikes. The actions described in Fig. 7 shows that smaller power is required to drive the DC motors of the mobile robot model.

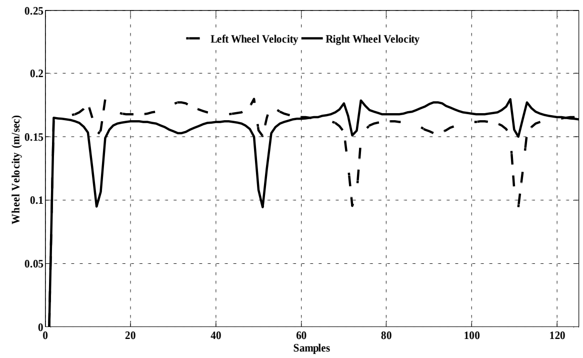


Figure (7). The right and left wheel action velocity.

The mean linear velocity of the mobile robot is equal to 0.135 m/sec, and the maximum peak of the angular velocity is equal to ± 0.5 rad/sec, as shown in Fig. 8.

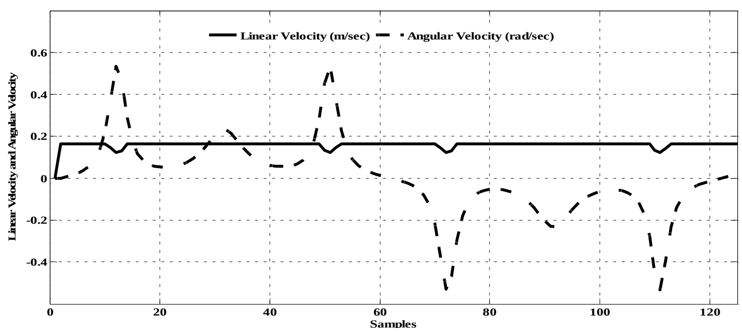
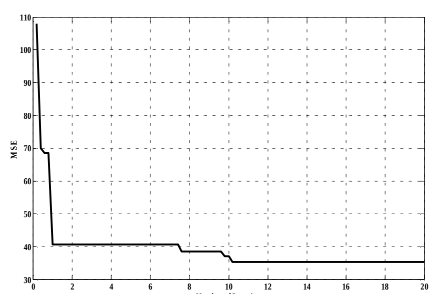


Figure (8).The linear and angular velocity.

Mean Square Error (MSE) is used as the performance index in the proposed control methodology and it is clear by showing the convergence errors of the pose trajectory and orientation for the robot model motion at 20 iterations, as shown in Fig. 9.



Figure(9). The performance index (MSE).

Figure 10 shows the effectiveness of the proposed cognitive PID neural control algorithm based on slice genetic algorithm in terms of the convergence of the pose trajectory and orientation errors for the robot model motion. The mean-square error for each component of the state error $MSE(x_e, y_e, q_e)$ is equal to (0.00131, 0.0029, 1.177).

(a)

(b)

(c)

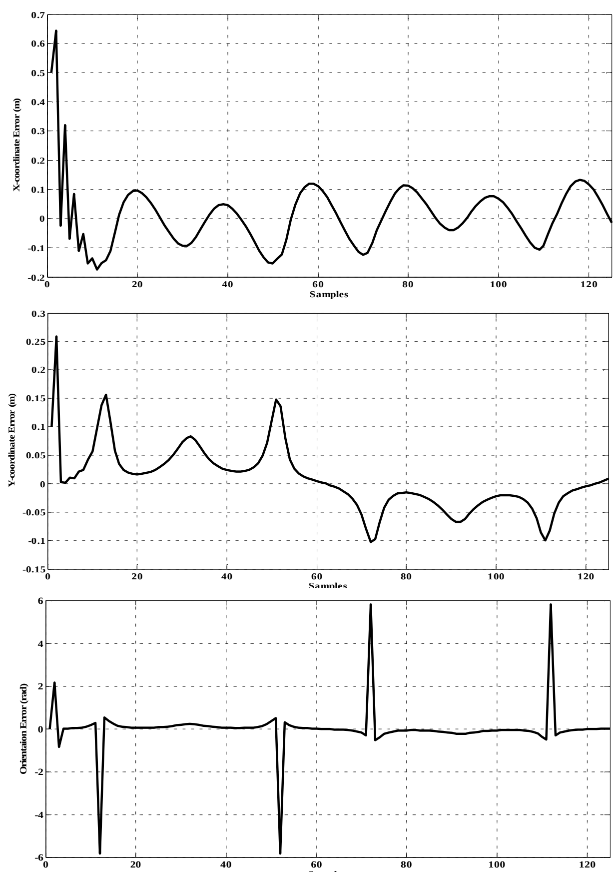


Figure (10). Position tracking error (a) in X- coordinate; (b) in Y-coordinate; (c) Orientation tracking error.

The optimized auto-tuning based on slice genetic algorithm is used for tuning the parameters of the cognitive PID neural controller (k_x, k_y, k_q) which has demonstrated, as shown in table 1.

Table (1). The cognitive PID Control Parameters.

kp_x	ki_x	kd_x	kp_y	ki_y	kd_y	kp_q	ki_q	kd_q
0.23	0.62	0.73	0.32	0.17	0.82	0.33	0.72	0.25

In order to investigate the applicability of the proposed tuning control methodology, experiments have executed by using mobile robot from Parallax Company type Eddie mobile robot, as shown in Fig. 11. which is equipped with LabVIEW package guided.

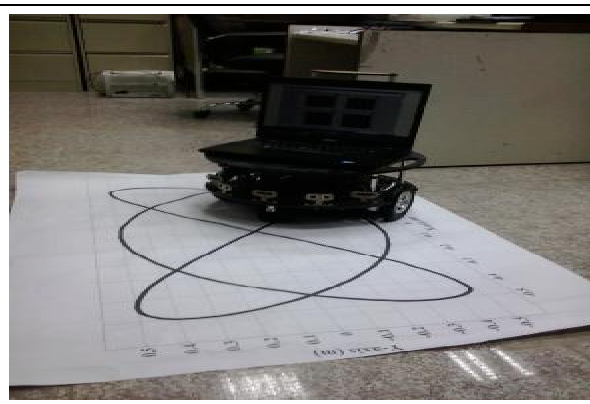
Figure(11). Eddie mobile robot for the experiments [18].

In the experiments, trajectory tracking controller is applied on real Eddie mobile robot in order to validate the controller adaptation, robustness and effectiveness in terms of minimum tracking error and in generating best velocity control action despite of the presence of bounded external disturbances.

The control data are transmitted to the Eddie mobile robot model, which admits right wheel velocity and left wheel velocity as input reference signals by using wire communication after and this is done after data conversion from MATLAB M-file format to LabVIEW package version 2010 format in the Eddie mobile robot.

Velocities commands sent by the computer represented as coded messages which are recognized by microcontroller. Based on received characters, the microcontroller creates control actions for servo motors. The output voltages of the two encoder sensors are converted to coded messages by microcontroller and sent to the personal computer in order to calculate the tracking error of the mobile robot during the motion.

The initial pose for the Eddie mobile robot starts at position (-0.1 and 0) meter and orientation $0.5p$ radian and shall follow the desired continuous trajectory, as show in Fig. 12. where the desired trajectory starts at position (0, 0, $0.5p$).



Figure(12). Real set-up experiment of Eddie mobile robot for continuoustrajectory tracking.

After 122 samples, the Eddie mobile robot has followed and finished the tracking of the desired path, as shown in Fig. 13a with small drifted from the desired trajectory and the distance of the trajectory did not exceed 6.941m. Figure 13b shows the actual orientation of the mobile robot with small error.

The tracking error in x-coordinate and y-coordinate were reasonably accurate, as shown in Fig. 13c. The velocity control action demonstrates how the Eddie mobile robot tries to correct the pose and orientation errors as shown in Fig. 13d.

From the simulation results and lab experiments, the cognitive PID neural control methodology based on SGA gives the best control result which is expected because of the precious ability of SGA in finding the optimal parameters of the proposed controller which depends on the previous values with smoothing step changes

The mean-square error for each component of the state error $MSE(x_e, y_e, q_e)$ for simulation results and experimental work is calculated, as shown in Table 2.

Table (2): The MSE for simulation results and experimental work.

Control Methodology	Simulation Results	Experimental Work
$MSE(x_e, y_e, q_e)$	(0.00131, 0.0029, 1.177)	(0.0019,0.0041,1.39)

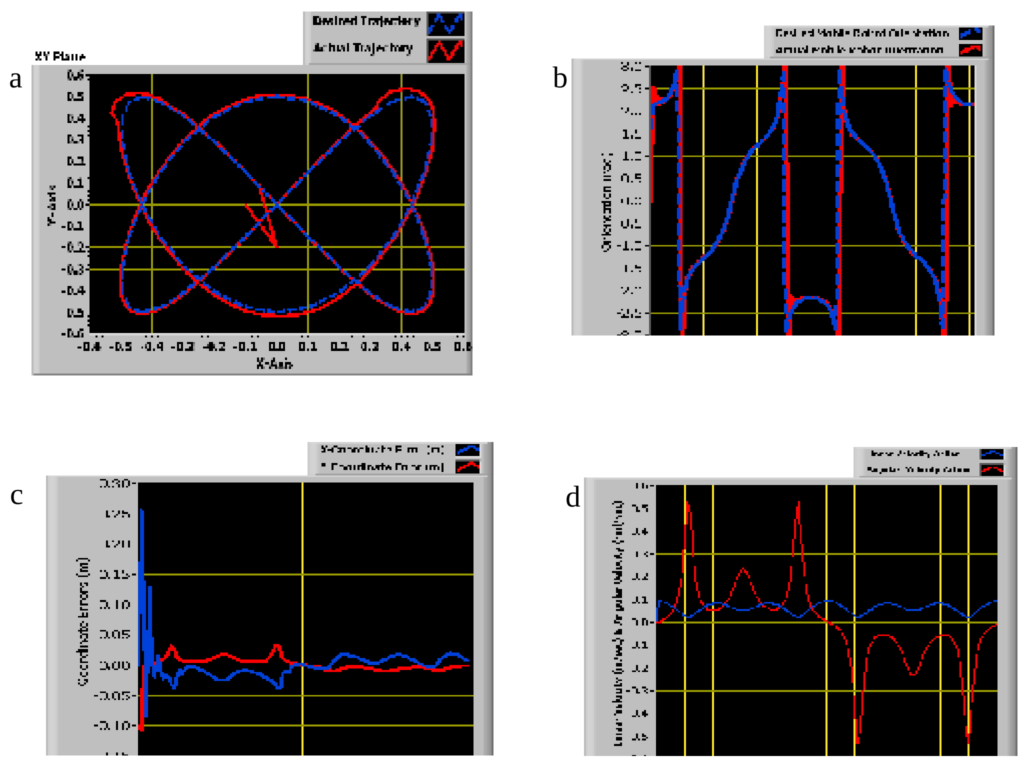


Figure (13). Practical results (a) desired and actual mobile robot trajectories; (b) desired and actual mobile robot orientations; (c) X-coordinate and Y-coordinate errors; (d) velocity control action.

The percentage of the mean square error between simulation results and experimental work can be shown in Table 3.

Table (3): The percentage of MSE between simulation results and experimental work.

(MSE of X-coordinate) 100%	31.5%
(MSE of Y-coordinate) 100%	29.3%
(MSE of Orientation) 100%	15.3%

The difference between simulations results and experimental results caused by the residual errors in the experimental results due to the inherent friction present in the real system, especially during tracking the continuous gradient path and modelling errors, due to the difficulty of estimating or measuring the geometric, kinematics or inertial parameters, or from incomplete knowledge of the system components.

CONCLUSIONS

The cognitive PID neural controller with slice genetic algorithm technique for MIMO differential wheeled mobile robot motion model has been presented in this paper.
The Matlab simulation results and the LabVIEW experimental work on trajectory tracking controller for the Eddie mobile robot which shows preciously that the proposed tuning control algorithm has the following:

- Fast and stable tuning control gain parameters with a minimum number of fitness evaluations.
- Effective minimization capability of tracking errors to follow a desired continuous gradients path.
- Efficiency of generating smooth and optimum suitable velocity commands, without sharp spikes.
- Robustness of trajectory tracking when unmodeled kinematic disturbances have been added to the system.

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