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A Cognition Path Planning with a Nonlinear Controller Design for Wheeled Mobile Robot Based on an Intelligent Algorithm

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ABSTRACT

This paper presents a cognition path planning with control algorithm design for a nonholonomic wheeled mobile robot based on Particle Swarm Optimization (PSO) algorithm. The aim of this work is to propose the circular roadmap (CRM) method to plan and generate optimal path with free navigation as well as to propose a nonlinear MIMO-PID-MENN controller in order to track the wheeled mobile robot on the reference path. The PSO is used to find an online tune the control parameters of the proposed controller to get the best torques actions for the wheeled mobile robot. The numerical simulation results based on the MATLAB package show that the proposed structure has a precise and highly accurate distance of the generated reference path as well as it has obtained a perfect torque control action without spikes and no saturation torque state that leads to minimize the tracking error for the wheeled mobile robot.

Key Words: Path Planning, PID controller, Modified Elman Neural Network; Mobile Robot; PSO Algorithm

تخطيط مسار مدرك مع تصميم مسيطر لأخطي لعجلات الإنسان الآلي مبني على أساس الخوارزمية الذكية

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الخلاصة

أن هذا البحث يقدم تخطيط مسار مدرك مع تصميم خوارزمية التحكم لعجلات الإنسان الآلي مبنيا على أساس خوارزمية حشد الجسيمات الامثلية. أن الهدف من هذا العمل هو اقتراح خريطة الطريق الدائرية لتخطيط ولتوليد المسار الأمثل مع ملاحة حرة وكذلك اقتراح طريقة التحكم (MIMO-PID-MENN) اللاخطية لكي يتبع الإنسان الآلي المتحرك المسار المحدد. أن خوارزمية

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حشد الجسيمات الامثلية استخدمت في هذا البحث لإيجاد وتنغيم قيم العناصر المثلى للمسيطر والتي من خلالها نحصل على أفضل أشارة فعل للإنسان الآلي المتحرك. من خلال نتائج المحاكاة العددية باستخدام الحقيبة البرمجية الماتلاب, تبين أن الهيكلية المقترحة تمتلك ضبط ودقة عالية في توليد المسار المرغوب و بالإضافة الى ذلك الحصول على أفضل عزم مسيطر بدون نتوأ ولا حالة الإشباع مما يؤدي الى تقليل الخطأ ألتتابعي للإنسان الآلي.

الكلمات الرئيسية: تخطيط مسار, مسيطر PID , الشبكة العصبية يلمن المعدلة, الإنسان آلي, خوارزمية حشد الجسيمات الامثلية.

1. INTRODUCTION

The robotics field has witnessed a rapid development in the sciences field like building, designing, and researching. The new mobile robots serve many practical purposes such as industry, weather forecasting, militarily, and domestically, **Malu** and **Majumdar, 2014**. Moreover, the mobile robots can do different jobs that are very dangerous to people like mining, defusing bombs, exploring shipwrecks and handling machines, **Murashov, et al., 2016.**

In general, to find the optimal or shorter path between two points, the robot uses the robotic path planning mechanism, where the optimum path could be the path that optimizes or minimizes the amount of braking and the amount of turning, **Kumar** and **Dewangan, 2016**. Moreover, the robot has to find the optimal path that enables randomly performing and continuous motion of robot from its initial configuration to the final configuration without any colliding or collapse with any obstacles available in its path or environment, **Kumar** and **Dewangan, 2016**.

In addition to that, the operation of an autonomously is the robot has to be capable of interacting with its environment in an intelligent way. Which implies that an autonomous robot must be able to capture information about the environment and then perform actions based on that information, **Raja** and **Pugazhenthi, 2012.**

The fundamental tasks in path planning are as follows: obstacle avoidance and path optimization. The robot path planning methods could be classified into different kinds based on different situations depending on the environment where the robot is located. Therefore, the path planning methods can be classified into two types as follows, **Reshamwala** and **Vinchurkar, 2013**.

- **Global Path Planning**

This approach can be used when the environment is completely static and known, therefore, this mechanism generates a complete path from the starting point to its destination point before the mobile robot starts its motion or work offline path planning, **Janis** and **Bade, 2016**.

- **Local Path Planning**

This method is used when the environment is not completely known, where the path planning is done while the robot is moving. The local path planning algorithm is capable of changing the path while moving with respect to the changes in an environment suitable for on-line implementation, **Janis** and **Bade, 2016**.

In recent years, the mobile robot navigation consists of three basic problems: tracking a reference trajectory, following a path, and point stabilization, **Fierro** and **Lewis, 1995**. Therefore, many researchers have proposed solutions to solve these problems such as different types of evolutionary techniques as Particle Swarm Optimization (PSO) as in, **Su, et al., 2015**, Ant and Bees Colony Optimization as in, **Contreras-Cruz, 2015,** and Genetic Algorithm as in, **Pandey, et al., 2017**, have been widely used to plan and generate the reference path for solving the problems of static and dynamic obstacles in the environment. On the other hand, many types of control algorithms techniques have been proposed to solve the mobile robot motion control for generating an optimal control action that leads to track the reference path with minimizing the tracking pose error of the wheeled mobile robot. These control algorithms include the fuzzy logic controller, **Omran, et al., 2016**, neural networks controller, **Al-Araji, 2014**, adaptive back-stepping controller, **Al-Araji, 2014**, adaptive sliding mode controller, **Xing, et al., 2016**, predictive controller, **Thinh, et al., 2016**, and nonlinear PID and fractional order PID neural controllers, **Al-Araji, et al., 2011; Al-Araji** and **Thamir, 2016**.

The main core of the motivation for this work is to plan reference path with static obstacles avoidance for the mobile robot and to track the reference path by generating the suitable control action without a saturation torque action state and no spike actions.

The main points of the contribution of this research are described after a comparative study with different nonlinear controllers, as follows:

- The cognition reference path can generate an optimal path with high accuracy based on the proposed circular roadmap (CRM) method to achieve the minimum distance with obstacles avoidance.
- The MIMO-PID-MENN with the PSO algorithm has derived the control law equation in order to generate the perfect torque action and to follow the reference path.
- Tracking different reference paths to confirm the capability of the proposed cognitive structure in terms of minimizing the tracking error of the mobile robot platform.
- Adding a dynamic disturbance to investigate the robustness performance of the proposed controller.
- Changing the initial pose state to verify the adaptation performance of the proposed controller.

This paper can be organized as follows: Section 2 describes the mathematical model of the dynamic mobile robot system. Section 3 derives the proposed cognition structure. Section 4 presents the numerical simulation results of the cognitive. In section 5 the conclusions are drawn.

2. NON-HOLONOMIC WHEELED MOBILE ROBOT MODEL

The non-holonomic wheeled mobile robot system is shown in **Fig.1** and it consists of a cart with two driving wheels mounted along the same axis, and one caster wheel in the front or rear the platform for stabilizing the mobile robot. The motion of the robot is determined by the two independent actuators DC motors that providing torque to the two wheels of the mobile robot. The mass center of the robot is located at point c, **Tian, et al., 2009**.

The kinematic model of the wheeled mobile robot is represented by Eq. (1), **Al-Araji, et al., 2011**, as follows:

$$\begin{bmatrix} x^{\bullet}(t) \\ y^{\bullet}(t) \\ \theta^{\bullet}(t) \end{bmatrix} = \frac{r}{2} \begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ \frac{2}{L} & -\frac{2}{L} \end{bmatrix} \begin{bmatrix} \omega r(t) \\ \omega l(t) \end{bmatrix} \tag{1}$$

Where: ωr and ωl are the angular velocity of the right and left wheel respectively. $x^{\bullet} and\ y^{\bullet}$ are the velocity of the robot in the direction of X-axis and Y-axis respectively; r: Radius of each driving wheel (m); L: Distance separating the two driving wheels; θ: The angle of rotation of the robot measured from X-axis.

For pure rolling and non-slipping constraints for the mobile robot as in Eq. (2), **Dagher** and **Al-Araji, 2014.**

$$\begin{bmatrix} -\sin\theta & \cos\theta(t) \end{bmatrix} \begin{bmatrix} x^{\bullet} \\ y^{\bullet} \end{bmatrix} = 0 \tag{2}$$

The dynamic model of the mobile robot, which is based on Euler Lagrange formulation, **Al-Araji** and **Yousif, 2017**, is illustrated as follows:

$$\begin{bmatrix} M & 0 & 0 \\ 0 & M & 0 \\ 0 & 0 & I \end{bmatrix} \begin{bmatrix} \ddot{x} \\ \ddot{y} \\ \ddot{\theta} \end{bmatrix} + \tau d = \frac{1}{r} \begin{bmatrix} \cos\theta & \cos\theta \\ \sin\theta & \sin\theta \\ \frac{L}{2} & \frac{-L}{2} \end{bmatrix} \begin{bmatrix} \tau_L \\ \tau_R \end{bmatrix} + \begin{bmatrix} -\sin\theta \\ \cos\theta \\ 0 \end{bmatrix} \lambda \tag{3}$$

where: τ_L is the left wheel torque; τ_R is the right wheel torque; M is the mobile robot's mass; I is the mobile robot's inertia; λ is the constraint forces and τ_d is bounded dynamic disturbances.

3. COGNITION STRUCTURE DESIGN

In this work, the cognition structure is to plan optimal smooth reference path for a mobile robot in order to avoid the static obstacle in the environment, then to track the reference path by using a nonlinear MIMO-PID-MENN controller. The proposed cognition structure can be described as shown in **Fig. 2**. The proposed structure consists of two layers:

a) Cognition reference path planning.
b) Nonlinear MIMO-PID-MENN controller.

3.1 Cognition Reference Path Planning

The goal of the cognition reference path planning is to plan an optimal smooth reference path for the mobile robot from a starting point to the target point in the environment with collision-free navigation. The proposed circular roadmap methodology for planning the reference path for a mobile robot is classified into classical approach when the environment has static obstacles and includes cell decomposition, mathematical programming or roadmap. To achieve the operation of this proposed methodology as shown in **Fig. 2** it needs the mobile robot model and the dimensions of the obstacle as circular shape in order to avoid the accident between the platform of the mobile robot and the static obstacle where the distance between two circular obstacles should be greater than the width of the mobile robot platform. Then the optimal reference path equation is generated. The generated desired path equation based on the proposed CRM methodology can be described in the following flowchart as shown in **Fig. 3**.

3.2 Nonlinear MIMO-PID-MENN Controller Design

This section focuses on the new structure of the nonlinear MIMO-PID-MENN controller design for the wheeled mobile robot based on the modified Elman recurrent neural network as shown in **Fig. 4**. The feedback torque control action is very important in the cognition structure because it is necessary to track the reference path and stabilize the tracking pose error of the mobile robot when the actual pose of the mobile robot drifts from the reference path in the environment.

The new structure of MIMO-PID-MENN controller which constructed from four layers each has its own operation as explained as follows, **Al-Araji, 2012.**

- Input Layer: it works as a buffer i.e. pass the data without any modification.

- Hidden layer: it is the active layer with the non-linear activation functions.
- Context layer: it is a memory layer without activation functions.
- Output layer: it represents a linear collector unit which adds all the fed signals.

The modified Elman neural network weights notation are: $kp_{x,y,\theta}$, $ki_{x,y,\theta}$ and $kd_{x,y,\theta}$ hidden layers weights. $Vc_{1,2}$**:** Context layers weight. Li **:** Linear node as a scaling factor and it is equal to 1. H **:** Sigmoid nonlinear node. $h_c^o(k)$: Context unit output. $h(k)$: Hidden unit. α **:** Self-connections feedback gain it is represented randomly between (0 to 1). β: Connection weight from the hidden layer to the context layer it is represented randomly between (0 and 1).

The capabilities of the modified Elman neural network structure give the new structure of the controller many abilities such as fast learning; high adaptation performance; high order control performance and this is due to the context units in MENN which memorizes the previous activations of the hidden units; good dynamic characteristic; no output oscillation and strong robustness performance due to the self-connection in the context units which increase the order of the controller model.

The control law of the right wheel torque and left wheel torque for the mobile robot platform depends on the x-y position errors and the orientation error as in Eqs. (19) and (20) respectively.

$$\tau_R(k) = o_x - o_y + h_{c1}(k)V_{c1} \tag{19}$$

$$\tau_L(k) = o_\theta - o_y + h_{c2}(k)V_{c2} \tag{20}$$

Where:

$$h_c^o(k) = \alpha h_c^o(k-1) + \beta \tau_{R.L}(k-1) \tag{21}$$

The modified Elman neural networks outputs based on the nonlinear relationship of the Sigmoid activation function is given as in Eq. (22).

$$\mathrm{O}_{x,y,\theta} = \frac{2}{1-\exp^{-net_{x,y,\theta}}} - 1 \tag{22}$$

The summation of each node can be written as follows:

$$net_x(k) = kp \times e_x(k) + ki \times (e_x(k) + e_x(k-1)) + kd \times (e_x(k) - e_x(k-1)) \tag{23}$$

$$net_y(k) = kp \times e_y(k) + ki \times (e_y(k) + e_y(k-1)) + kd \times (e_y(k) - e_y(k-1)) \tag{24}$$

$$net_\theta(k) = kp \times e_\theta(k) + ki \times (e_\theta(k) + e_\theta(k-1)) + kd \times (e_\theta(k) - e_\theta(k-1)) \tag{25}$$

Where $ex(k)$, $ey(k)$, $e\theta(k)$ are the error inputs signals.

Therefore, we needed eleven weight parameters of the controller and we used the PSO algorithm to tune these parameters as in Eqs. (26) and (27):

$$\Delta\overline{V}_i^{k+1} = \Omega\Delta\overline{V}_i^{k} + c_1 r_1 (pbest_i^k - \overline{V}_i^{k}) + c_2 r_2 (gbest^k - \overline{V}_i^{k}) \tag{26}$$

$$\overline{V}_i^{k+1} = \overline{V}_i^{k} + \Delta\overline{V}_i^{k+1} \tag{27}$$

Where:

$\Delta\overline{V}_i^{k+1}$ is the i^{th} particle's velocity (*kp ki, kd,* and *Vc*) at k^{th} iteration; V_i^k is the i^{th} particle's position (*kp, ki, kd,*and *Vc*) at k^{th} iteration; Ω : is the inertia weight factor and equal to 0.73; c_1 and c_2 are the

positive values equal to 1.49; r_1 and r_2 are random values (0 to 1); $pbest_i$ is the i^{th} particle's best previous weight; $gbest_d$ is the best particle from the overall population.
The performance index of the evaluation for the MIMO-PID-MENN controller is used as the mean square error function as in Eq. (28) **Al-Araji, et al., 2011**.

$$MSE = \frac{1}{Nit}\sum_{i=1}^{Nit}[(x_{ref} - x)^2 + (y_{ref} - y)^2 + (\theta_{ref} - \theta)^2 \quad (28)$$

Nit: is the number of iterations.

4. SIMULATION RESULTS

The MATLAB package is used as a numerical simulation m.file to verify the cognition structure based on a new nonlinear MIMO-PID-MENN controller for the mobile robot in order to plan and track the reference path with free-navigation. The parameters of the Eddie mobile robot platform are taken from, **Al-Araji** and **Yousif, 2017**: M=12kg; I=1.536kg.m; r = 0.075m and L= 0.39m with sampling time equal to 0.2 sec
The first step in the cognition structure is carried out the proposed CRM methodology in order to get the optimal reference path and the second step is executed the path tracking based on the nonlinear MIMO-PID-MENN controller with PSO algorithm. The PSO algorithm is used in this work to get and tune the control parameters of the proposed nonlinear controller which leads to generate optimal and smooth torque control action and minimize the tracking pose error. The PSO parameters can be defined as in **Table 1** for each case.
Each particle has 11 weights because there are eleven parameters of (MIMO-PID- MENN) controller; and r1- r2 are random values between 0 and 1.

Case Study I

The mobile robot has initial pose as q (0) = [0, 20] cm. After applying the proposed CRM methodology in order to get the optimal path as shown in **Fig. 6**. It generated three paths to avoid the static obstacles as a first step, then the distances of these three paths between starting point to target point are (584.835, 599.204 and 648.961) cm respectively depending Eq. (18), so path1 is the optimal path because it has the shortest distance (584.835) cm. The second step is obtaining the reference path equation for the optimal path by using the fitting function which is obtained from the reference path equation as follows:

$$y(x) = 3.711\times10^{-8}x^4 - 2.631\times10^{-5}x^3 + 0.006992x^2 + 0.03306x + 1.456 \quad (29)$$

Then the third step in the cognition structure is applying the nonlinear MIMO-PID-MENN based on PSO algorithm to track the mobile robot the reference path based on the reference path equation as shown in **Fig. 7**.
The on-line Mean Square Error (MSE) has clearly improved the performance of the controller by showing the pose error convergence for the mobile robot motion at 400 steps, as shown in **Fig. 8**.
The effectiveness of the new nonlinear MIMO-PID-MENN controller response through generating smooth torque control action without saturation control action state in order to follow the reference path equation as shown in **Fig. 9.**
The linear and angular velocities responses for the non- holonomic wheel mobile robot are smooth without sharp spikes, as shown in **Fig. 10**.
Figs. 11. a, b, c show the high robustness and strong adaptation performances of the proposed cognition structure in terms of keeping on minimum tracking pose error for the wheeled mobile

robot platform because the effect of the bounded dynamic disturbances to the system that it is taken from $\overline{\tau d} = [0.01\sin(2t) \quad 0.01\sin(2t)]^T$ has been reduced effect.

Case Study II:

The mobile robot has initial pose as q (0) = [0,380] cm. After applying the proposed CRM methodology in order to get the optimal path based on the flowchart as shown in **Fig. 12**. Three paths are generated to avoid the static obstacles as a first step, then the distances of these three paths between the starting point to target point are (596.591, 604.056 and 670.761) cm respectively depending Eq. (18), so path1 is the optimal path because it has the shortest distance (596.591) cm. The second step is obtaining the reference path equation for the optimal path by using the fitting function which is obtained to the reference path equation as follows:

$$y(x) = 3.19\times10^{-8}x^4 - 4.173\times10^{-5}x^3 + 0.01824x^2 - 3.662x + 4.006 \quad (30)$$

The third step is applying nonlinear MIMO-PID-MENN to make the mobile robot follows the desired path, as shown in **Fig. 13**.

The effectiveness of the proposed controller response through generating smooth torque control action without saturation control action state to follow the reference path equation in minimum time as shown in **Fig. 14**. The linear and angular velocities responses for the non- holonomic wheel mobile robot are smooth without sharp spikes, as shown in **Fig. 15**.

Case Study III.

To verify the proposed CRM method is a powerful technique, **Fig. 16** shows the CRM method has added some virtual obstacles in order to achieve the steps for planning the path for the mobile robot which has initial pose as q(0) = [0,20] cm then generated three paths to avoid the static obstacles as a first step, then the distances of these three paths between starting point to target point are (585.853, 649.631 and 656.89) cm respectively depending Eq. (18), so path1 is the optimal path because it has the shortest distance (585.853) cm. The second step is obtaining the reference path equation for the optimal path by using the fitting function which is obtained to the reference path equation as follows:

$$y(x) = 3.488\times10^{-8}x^4 - 2.472\times10^{-5}x^3 + 0.006684x^2 + 0.04559x + 1.414 \quad (31)$$

The third step is applying nonlinear MIMO-PID-MENN to make the mobile robot follows the desired path as shown in **Fig. 17**.

The effectiveness of the proposed controller response through generating smooth torque control action without saturation control action state to follow the reference path equation in minimum time as shown in **Fig. 18.**

The linear and angular velocities responses for the non- holonomic wheel mobile robot are smooth without sharp spikes, as shown in **Fig. 19**.

5. CONCLUSIONS

The numerical simulation results of the proposed cognition circular roadmap methodology and nonlinear MIMO-PID-MENN controller based on the PSO algorithm is presented in this paper for the mobile robot system which shows the following capabilities:

- Highly accurate short reference path distance is obtained between the starting point and the target position for the mobile robot during working in obstacles environment.
- An on-line PSO algorithm is achieved for the control parameters of the proposed controller.

- The best torque action is generated without a saturation state.
- Tracking an excellent reference path with a minimum pose error is achieved.
- Strong adaptability performance when changing the initial pose for the mobile robot.
- High robustness performance when adding the bounded disturbances to the mobile robot.

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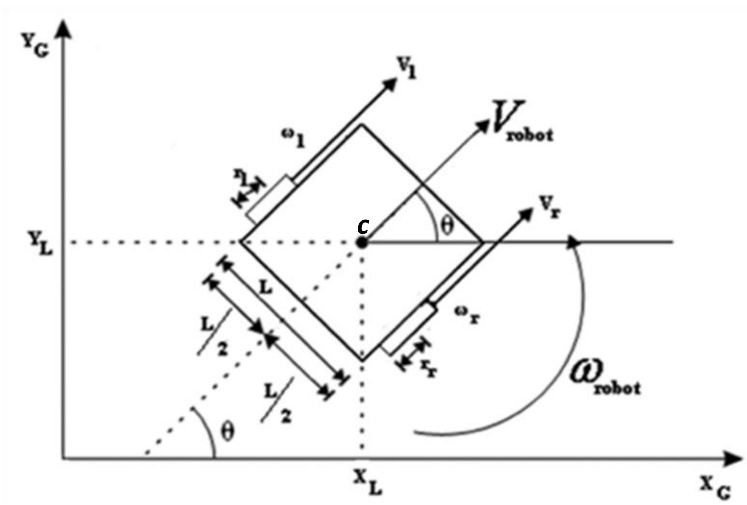


Figure 1. Model of the non-holonomic mobile robot.

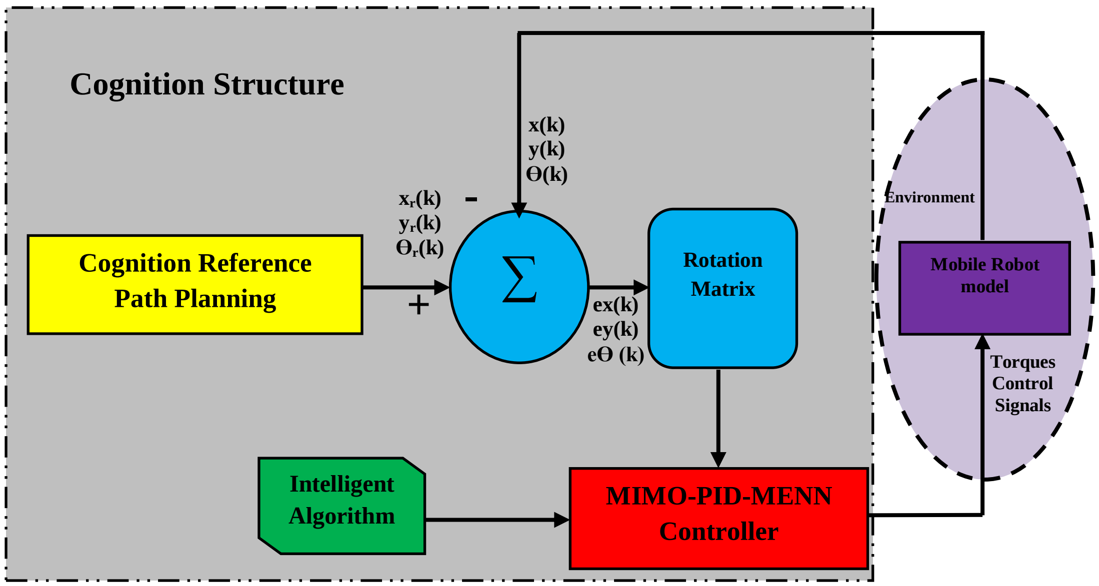


Figure 2. The cognition structure for the mobile robot system.

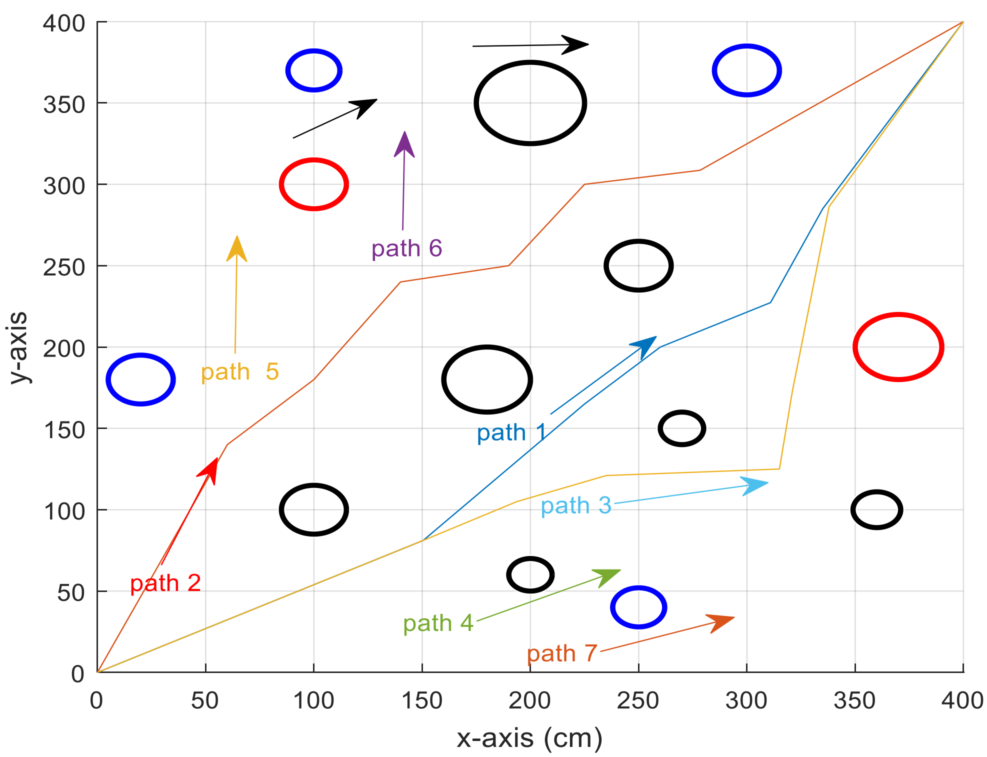
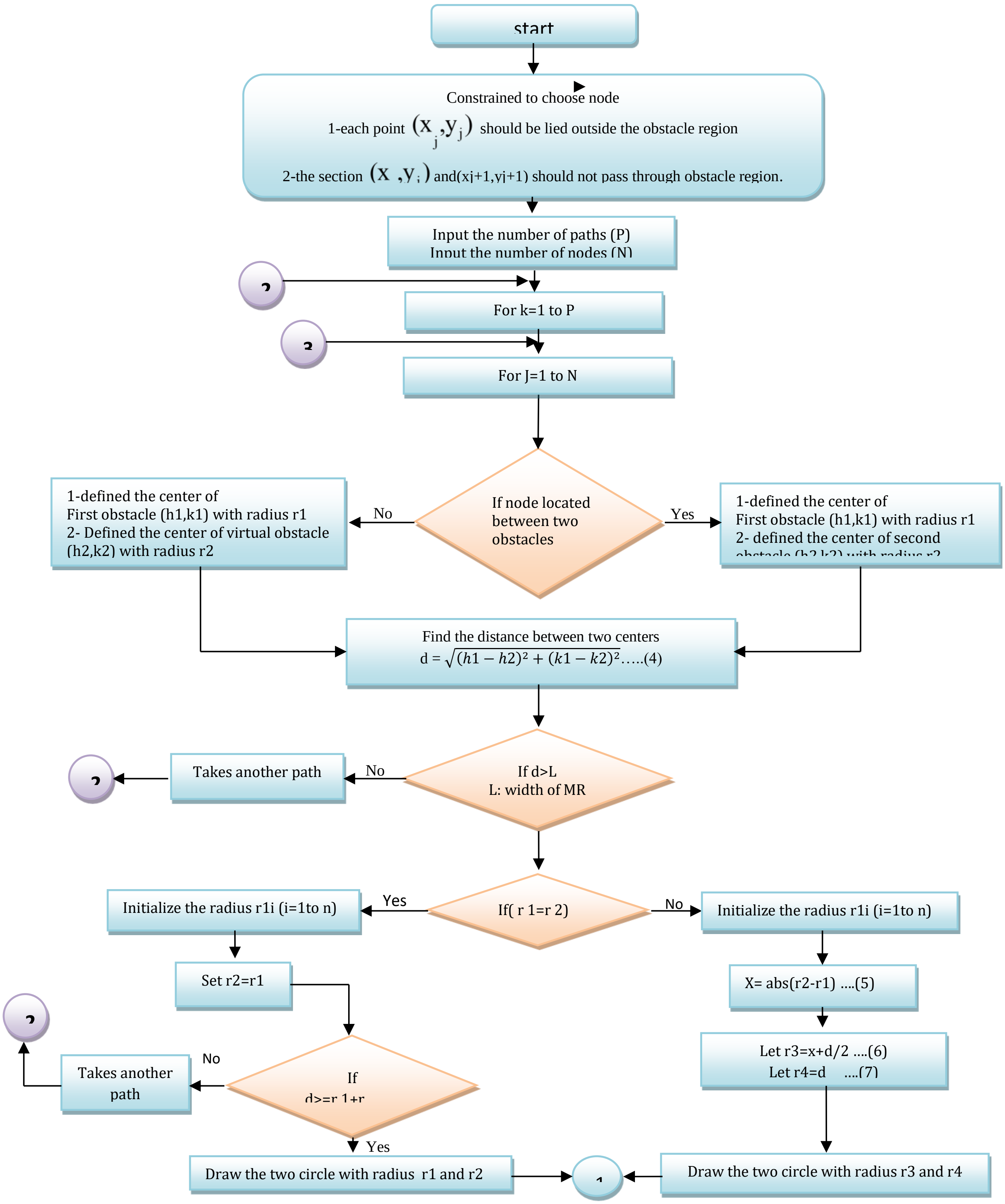


Figure 3. The generated reference path for the mobile robot based on the proposed CRM methodology.


start
Constrained to choose node
1-each point (x_j, y_j) should be lied outside the obstacle region
2-the section (x_j, y_j) and(xj+1,yj+1) should not pass through obstacle region.
Input the number of paths (P)
Input the number of nodes (N)
For k=1 to P
For J=1 to N
If node located between two obstacles
No
1-defined the center of First obstacle (h1,k1) with radius r1 2- Defined the center of virtual obstacle (h2,k2) with radius r2
Yes
1-defined the center of First obstacle (h1,k1) with radius r1 2- defined the center of second
Find the distance between two centers
$d = \sqrt{(h1-h2)^2+(k1-k2)^2}$.....(4)
If d>L
L: width of MR
No
Takes another path
If(r 1=r 2)
Yes
Initialize the radius r1i (i=1to n)
No
Initialize the radius r1i (i=1to n)
Set r2=r1
X= abs(r2-r1) ....(5)
Let r3=x+d/2 ....(6)
Let r4=d ....(7)
If
No
Takes another path
Yes
Draw the two circle with radius r1 and r2
Draw the two circle with radius r3 and r4

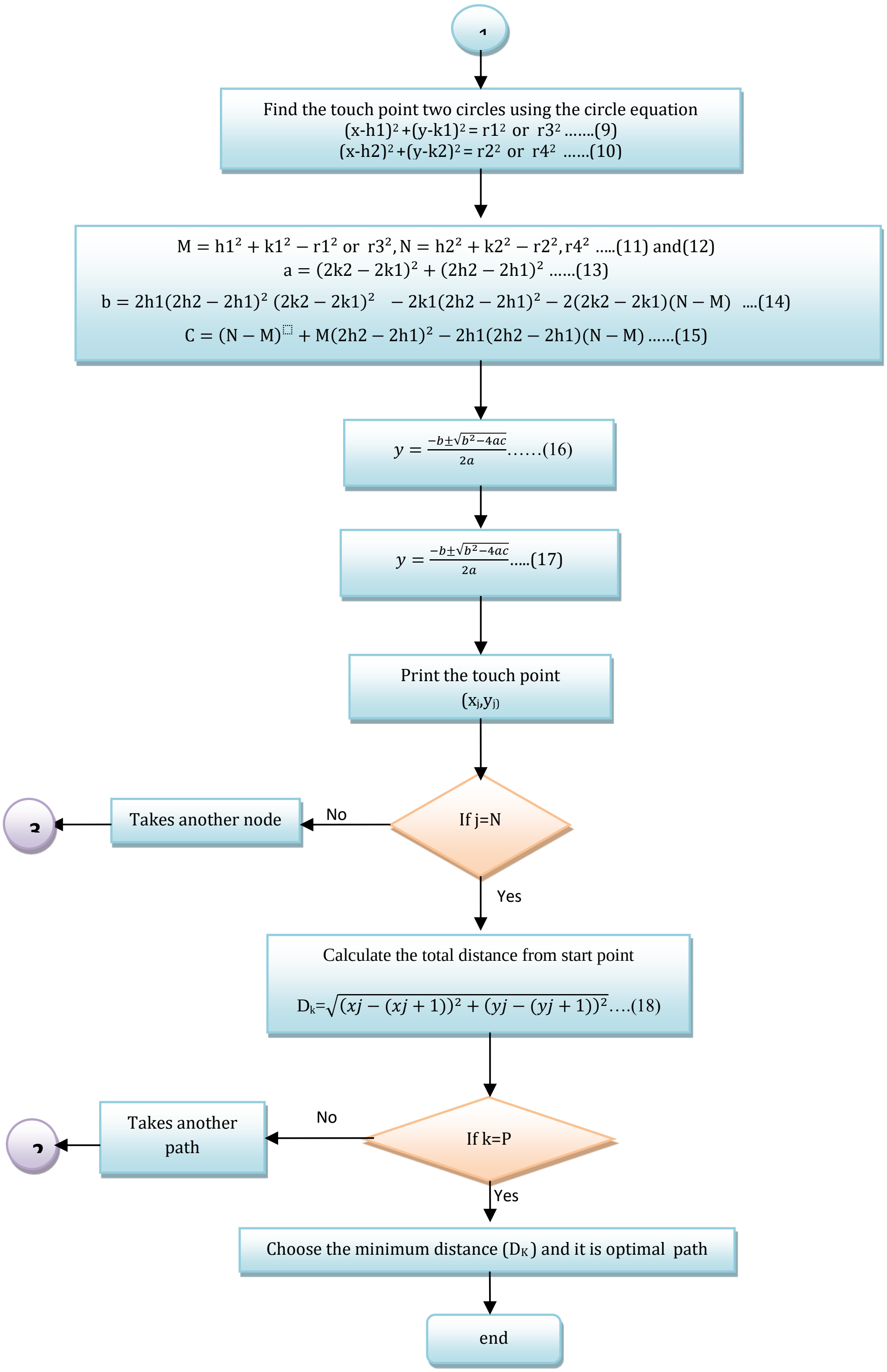


Figure 4. CRM method flowchart.

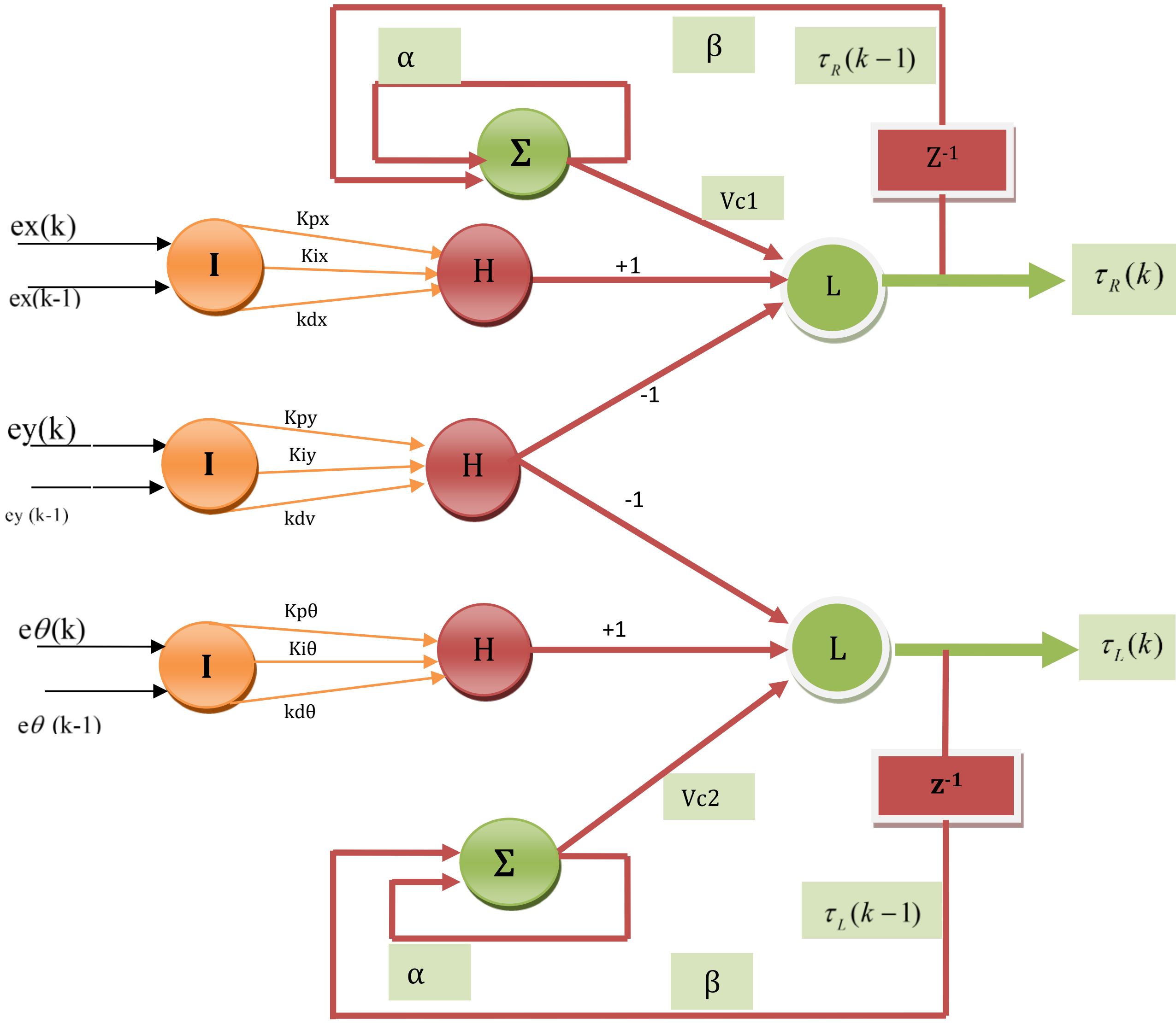


Figure 5. The new proposed of nonlinear MIMO-PID-MENN controller structure.

Table 1. The PSO Parameters for Cognition Structure.

Parameters	Case Study I	Case Study II	Case Study III
Number of The population of particle	20	10	15
Number of the iteration	20	15	15
Acceleration constant c1 and c2	1.49	1.49	1.49
Weight factor	0.73	0.73	0.73

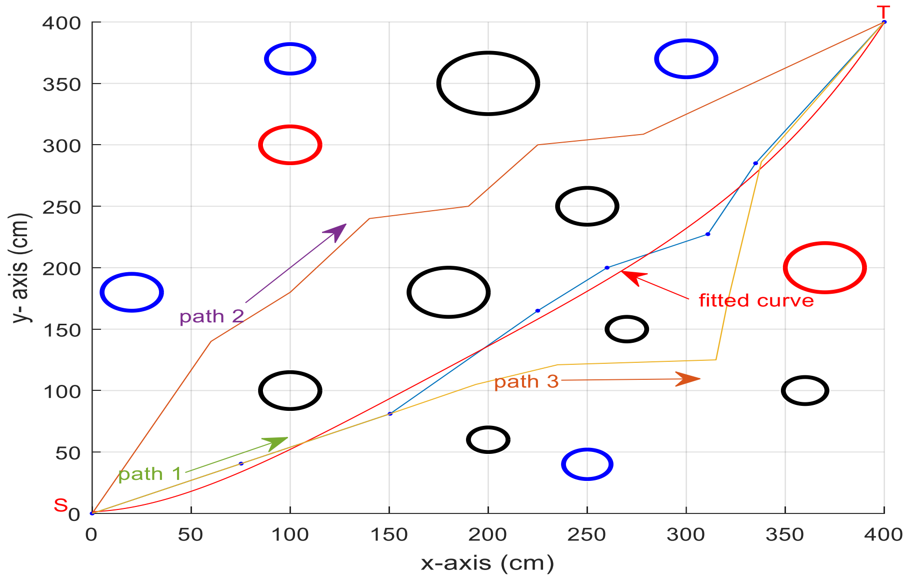


Figure 6. The optimal path generated for case I.

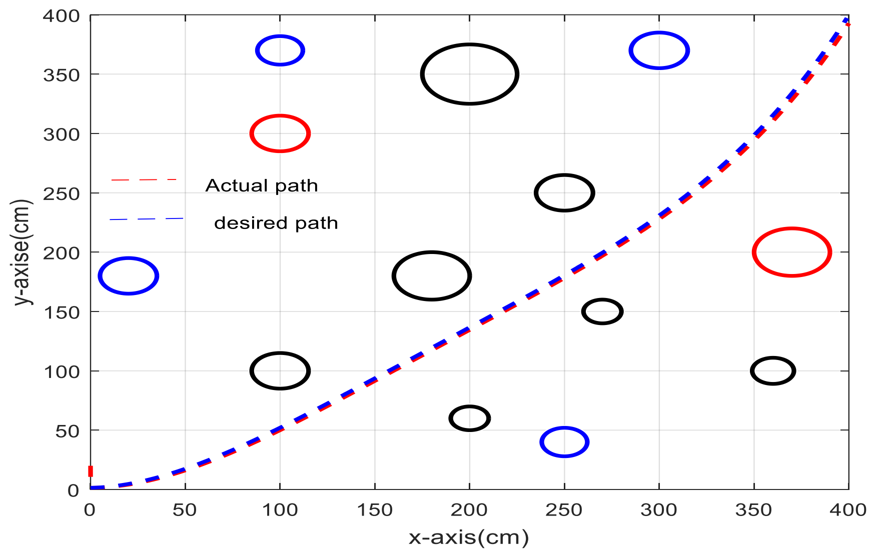


Figure 7. The reference path equation and actual path for mobile robot.

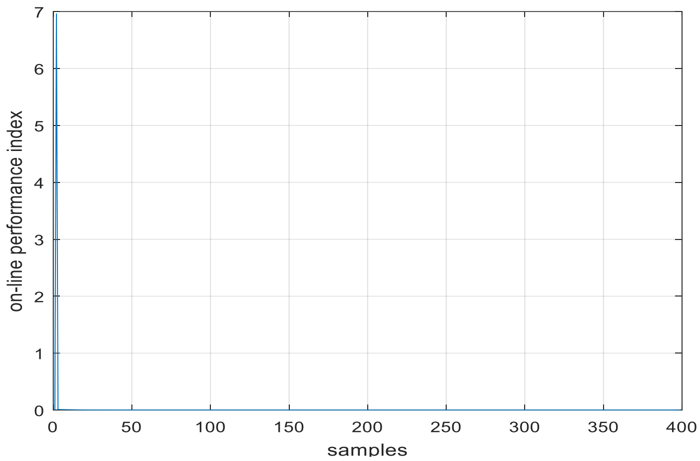


Figure 8. On-line performance index**.**

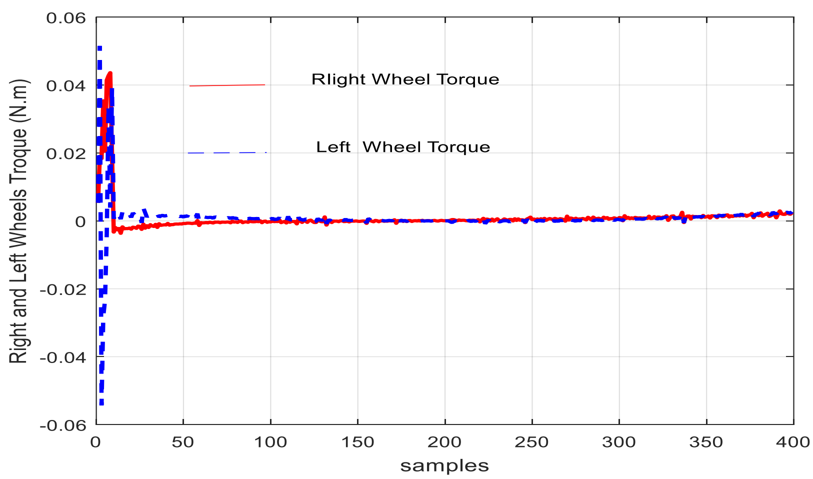


Figure 9. Torque Control Action.

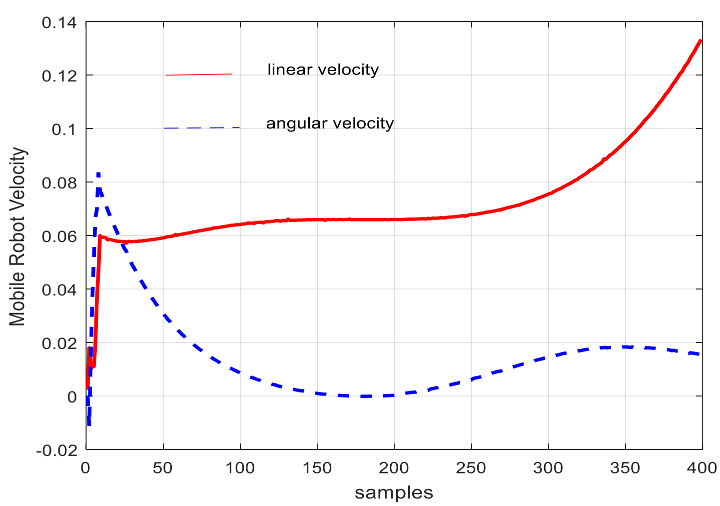
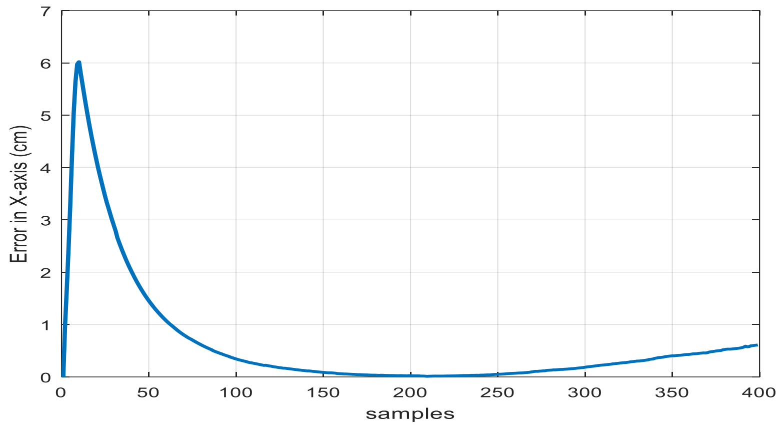
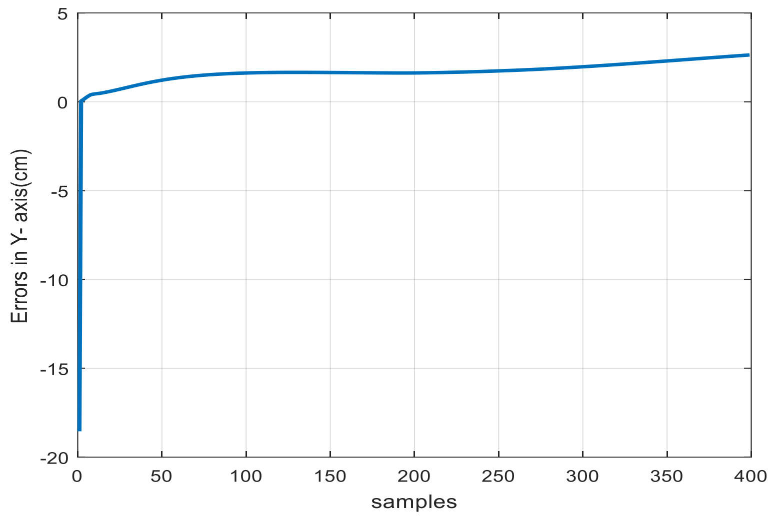


Figure 10. Linear and Angular Velocities of the Mobile Robot.

a



b



c

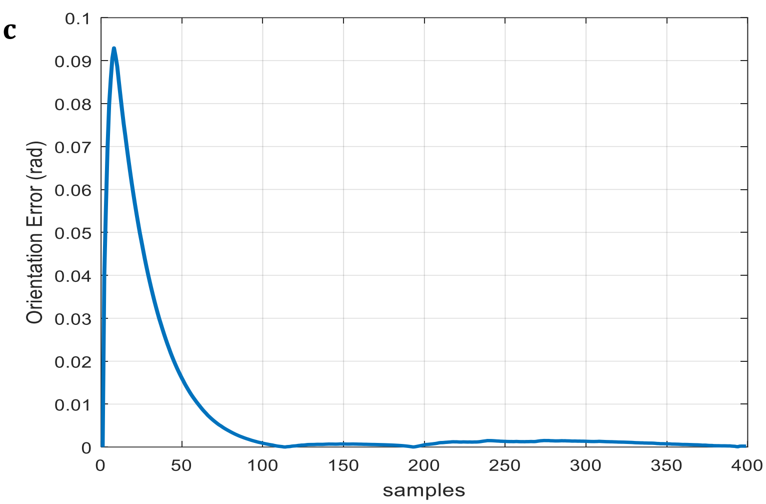


Figure 11. Pose error of the mobile robot: a) error in X-axis; b) error in Y-axis; c) orientation error.

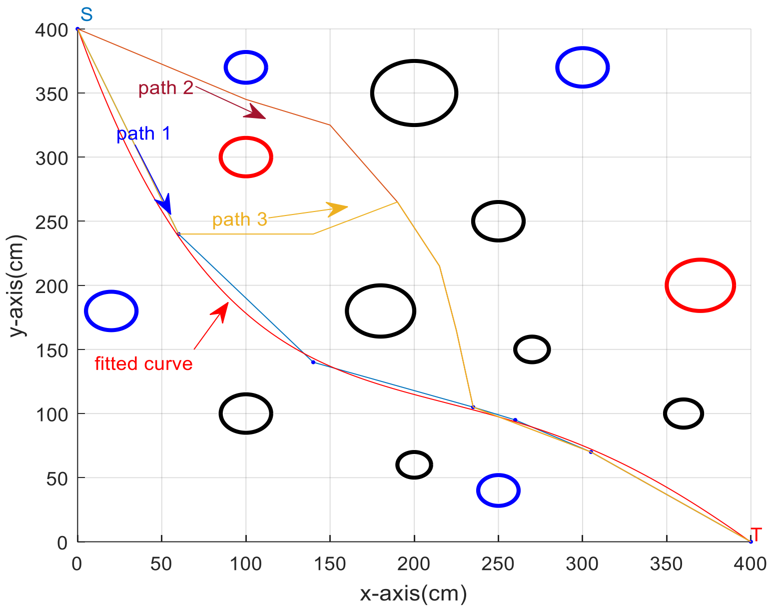


Figure 12. The optimal path generated for case II.

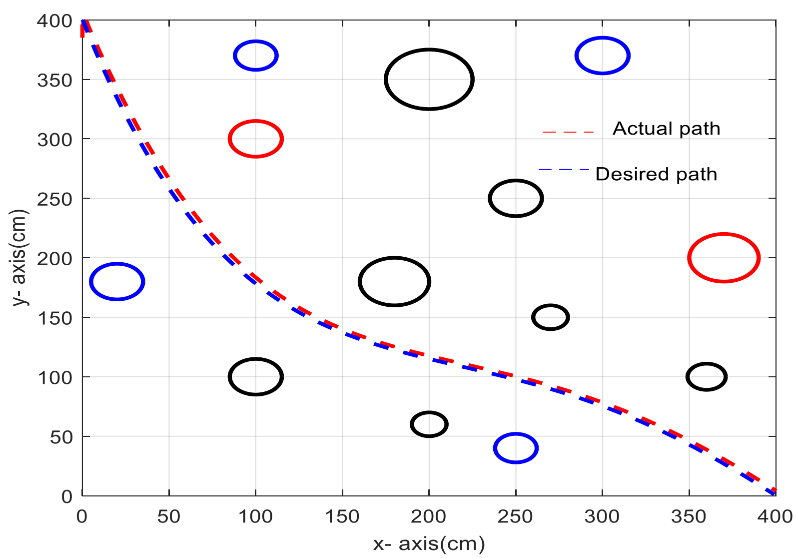


Figure 13. The reference path equation and actual path for mobile robot.

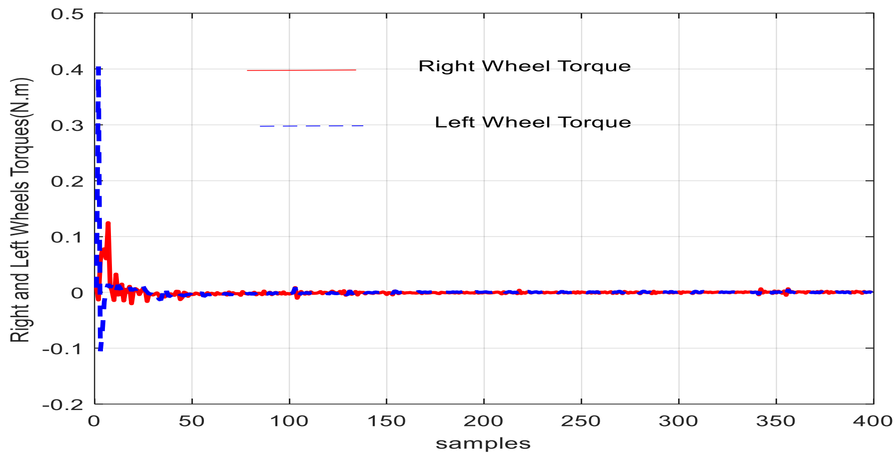


Figure 14. Torque control action.

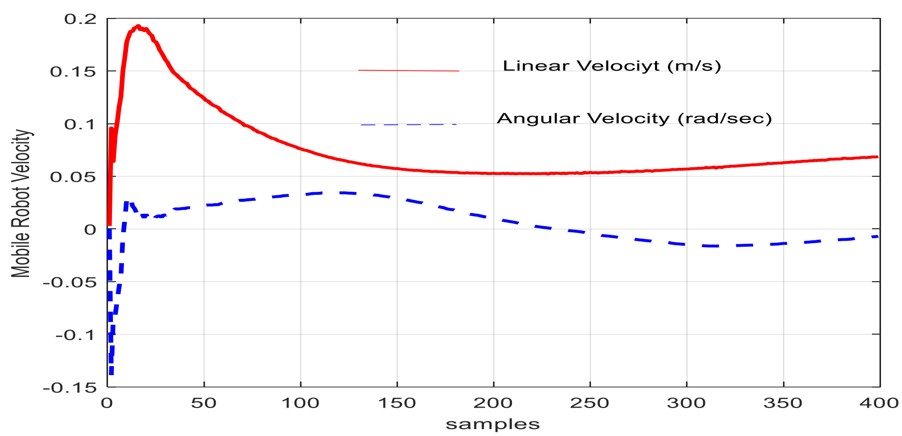


Figure 15. Linear and angular velocities of the mobile robot.

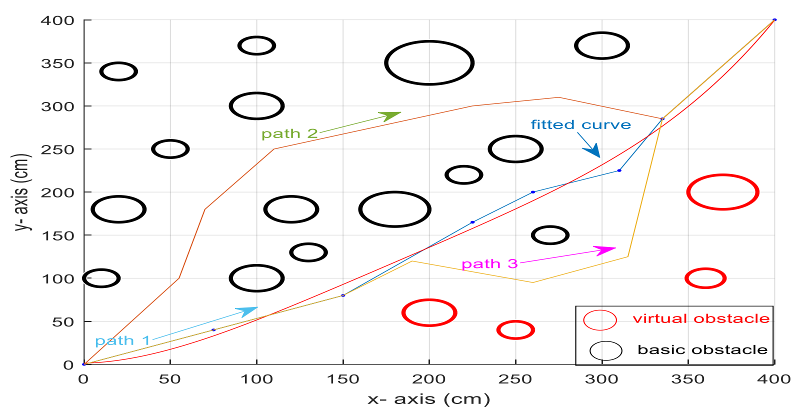


Figure 16. The optimal path.

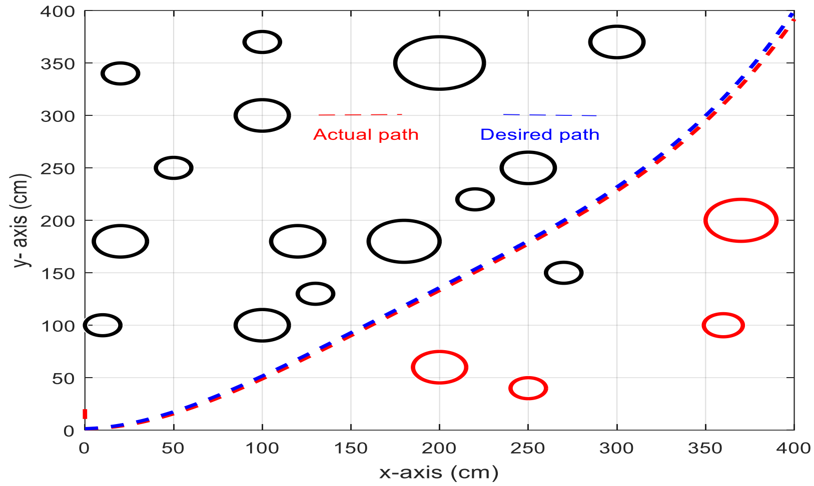


Figure 17. The reference path equation and actual path for mobile robot.

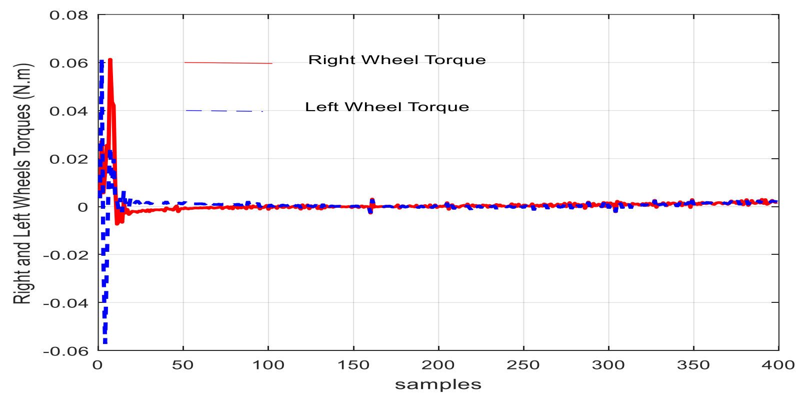


Figure 18. Torque Control Action.

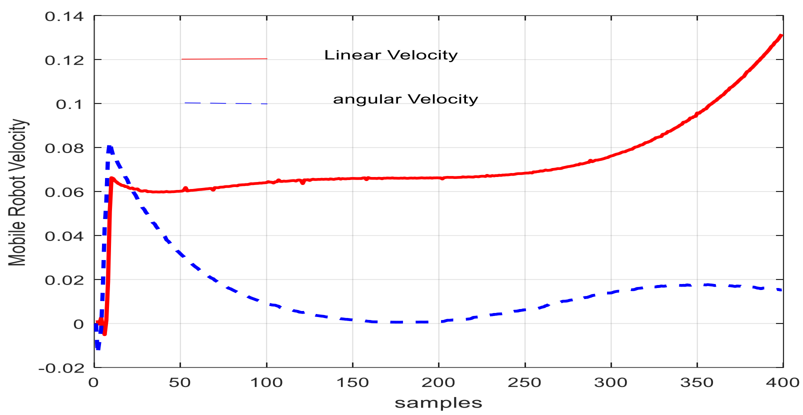


Figure 19. Linear and angular velocities of the mobile robot.