https://doi.org/10.21289/KSIC.2022.25.4.521

A Study on an Intelligent Motion Control of Mobile Robot Based on Iterative Learning for Smart Factory

Oh-Duck Im[1*], Hee-Jin Kim[2], Da-Bi Kang[3], Min-Chan Kim[3], Sung-Hyun Han[4]

〈Abstract〉

This study proposed a new approach to intelligent control of a mobile robot system by back properpagation based on multi-layer neural network. A experiment result is given in which some artificial assumptions about the linear and the angluar velocities of mobile robots from recent literature are dropped. In this study, we proposed a new thinique to impliment the real time conrol of he position and velocity of mobile robots. With the proposed control techinique, mobile robots can now globally follow any path such as a straight line, a circle and the path approaching th toe origin using proposed controller. Computer simulations are presented, which confirm the effectiveness of the proposed control algorithm. Moreover, practical experimental results concerning the real time control are reported with several real line constraints for mobile robots with two wheel driving.

Keywords : Real Time Control Implimentation, Intelligent Control, Iterative Learning, Smart Factory, Mobile Robot System

1* Main author, Navy Shipyard, Korea
E-mail: lim5d@daum.net
2 Author, Graduate Student, Dept. of Mechanical Eng., Graduate School, Kyungnam Univ., Korea
3 Author, Under Graduate Student, School of mechanical Eng., Kyungnam Univ., Korea
4 Author, Professor, School of Mechanical Eng., College Engineering, Kyungnam Univ.

1. Introduction

The control problem of mobile robot systems has attracted considerable attention among the control community recently. Attempts to control such systems are, however, deceptively simple. The challenge of this problem is reflected on the fact that a mobile robot in the place possesses three degrees of freedom of motion, which have to be controlled by only two control inputs and under the nonholonomic constraint. Several researchers have shown, based on Brockett's theorem, that such a system is open-loop controllable, but not stabilizable by pure smooth time-invariant feedback[1].

Recently, methods for solving this problem can be put into two categories. The first one is based on the motion planning by using the vision guided, environment prediction, artificial neural network, or other sensory information[2].

The second category is using the nonlinear system theorems for solving this problem, e.g., the hybrid control, the backstepping technique, the sliding model control, the fuzzy logic control, and the adaptive control, etc., In this category, two main research directions have been adopted for mobile robots. The first direction, started form Bloch et al. Uses the discontinuous feedback whereas the second one uses time-varying continuous feedback, which was first investigated by Samsom. Subsequent to these investigations, Pomet then proposed the feedback control laws. But they were to solve the regulation problem found to yield a slow asymptotic convergence. In order to obtain faster convergence, an alternative approach was proposed by M'Closkey and Murray in initially and taken up in several studies subsequently[3].

The tracking problem for mobile robots has also attracted as much attention among researches. Using Barbalet lemma or the backstepping method, robots could globally follow special paths such as circles and straight lines. Despite the apparent advancement of the above methods, there remains however, several main restrictions on their applications: (a) In the tracking problem, only some special cases are solved. (b) In other cases, for example, the tracking problem with the linear and the angular velocities approaching to zero remains unsolved[4][5].

In additional, it is preferred to solve the tracking problem and the regulation problem simultaneously using a controller, otherwise, there will be a need to switch between two controllers of different types. In this paper, both the tracking problem and the regulation problem of mobile robots will be solved simultaneously without any further assumptions except for some regular assumptions. Moreover, for the several constraint in control inputs are also taken into consideration in the tracking problem[6].

2. System Modelling

The mobile robots considered in this

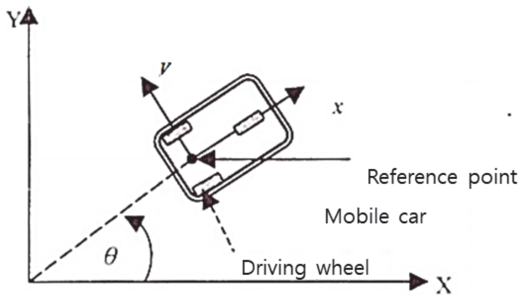

Fig. 1 A coorine frames of simplified mobile robot

paper, are a simplified model of the constraint on the movement of a rear car, see Fig. 1. The nonholonomic constraint for this simplified model is presented as following

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

that specifies the tangent direction along any feasible path for the robot and a bound on the curvature of the path. From the driver's viewpoint, there are two degrees of freedom for a general car: the accelerator and the steering wheel. Herein, we assume that the reference point lies in the midpoint of the rear wheels. We denote by v the linear velocity and by w the angular velocity of the mobile robot. Moreover, (x,y) are the Cartesian coordinates of the center of mass of the vehicle, and θ is the angle between the heading direction and the x-axis. Let us consider a simplified moblie robot model described as following[7].

$$\dot{x} = v\cos\theta,\ \dot{y} = v\sin\theta,\ \dot{\theta} = w$$

Notice that, in the plane, the mobile robot possesses three degrees of freedom of motion, which have be controller by only two control input and under nonholonomic constraint. When we consider the state vector (x, y, θ), it is rather straightforward to show that system is controllable in both position and orientation[8]. Unfortunately, we must confront a system where linearization results in a loss of controllability, although the nonlinear system is controllable. In particular, there are many researches, based on Brockett's theorem[9], showed that such a system is open-loop controllable, but not stabilizable by pure smooth time-invariant feedback[10]. R denotes the set of all real numbers and R^+ denotes the set of all nonnegative real numbers. Fistly, function f: $R_+ \to R$ is uniformly continuous if for any $\varepsilon > 0$. there exists a $\delta(\varepsilon) > 0$ such that if $|x_1 - x_2| < \delta$, with $x_1, x_2 \in R^+$, then $|f(x_1) - f(x_2)| < \varepsilon$. Secondly, Define the saturation function $sat_\delta(x)$ with $\delta > 0$ as

$$sat_\delta(x) = \begin{cases} x & |x| \le \delta \\ sgn(x)\delta & |x| > \delta \end{cases}$$

uppose the reference trajectory is described by next following equation

$$\begin{aligned} \dot{x}_r &= v_r\cos\theta_r \\ \dot{y}_r &= v_r\sin\theta_r \\ \dot{\theta}_r &= w_r \end{aligned} \tag{1}$$

where the desired linear velocity satisfying

$0 \le v_r\,(v_r = (\dot{x}_r^2 + \dot{y}_r^2)^{0.5}) < v_{\max}$ the bounded a and uniformly continuous, with $v_{\max}$ and $w_{\max}$ representing saturation bounds from practical restriction for control tracking case, i.e., $x \equiv x_r, y \equiv y_r, \theta \equiv \theta_r$, the equation (5) always holds. In this paper, main purpose to solve the following tracking problem.

To find saturation control laws for v and w with $|v| < v_{\max}, |w| < w_{\max}$ such that the mobile robot with the dynamic model (3) follows a reference trajectory $(x_r(t), y_t(t),)$. $(\theta_r(t))$.

That is,

$$\lim_{t\to\infty}|x(t)-x_r(t)|=0, \lim_{t\to\infty}|y(t)-y_r(t)|=0,$$
$$\lim_{t\to\infty}|\theta(t)-\theta_r(t)|=0.$$

Using the body frame, we define the error coordinates as following equation[12].

$$\begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_r - x \\ y_r - y \\ \theta_r - \theta \end{bmatrix} \quad (2)$$

Therefore, the tracking error model is obtained as

$$\begin{aligned} \dot{x}_e &= wy_e - v + v_r\cos\theta_e \\ \dot{y}_e &= -wx_e + v_r\sin\theta_e \\ \dot{\theta}_e &= w_r - w \end{aligned} \quad (3)$$

For convenience, we choose new coordinates and inputs as

$$\begin{bmatrix} x_0 \\ x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} \theta_e \\ y_e \\ -x_e \end{bmatrix}, \begin{bmatrix} u_0 \\ u_1 \end{bmatrix} = \begin{bmatrix} w_r - w \\ v - vcosx_0 \end{bmatrix} \quad (4)$$

System (4) can be rewritten as

$$\begin{aligned} \dot{x}_0 &= u_0 \\ \dot{x}_1 &= (w_r - u_0)x_2 + v_r\sin x_0 \\ \dot{x}_2 &= -(w_r - u_0)x_1 + u_1 \end{aligned} \quad (5)$$

With the new-coordinates (x_0, x_1, x_2), the tracking problem is now transformed to a stability problem. Throughout this paper, these coordinates (x_0, x_1, x_2) will be used to solve the tracking problem. More explicitly, by the invariance of coordinate transformations, of the (x_0, x_1, x_2) converge to zero.

$$\lim_{t\to\infty}|x(t)-x_r(t)|=0, \ \lim_{t\to\infty}|y(t)-y_r(t)|=0,$$
$$\lim_{t\to\infty}|\theta(t)-\theta_r(t)|=0.$$

3. The Control Scheme

3.1 The controltheory and stability

In this section, a globally tracking control algorithm with environmental constraint is presented using the backstepping method and the idea from the standard stability theory[13]. The stability of the closed-loop system is guaranteed without any further assumptions relating v_r and w_r.

$$\bar{I} = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}, \bar{I}_e = \begin{bmatrix} x_e \\ y_e \\ \theta_e \end{bmatrix}, \bar{I}_{r1} = \begin{bmatrix} x_r \\ y_r \\ \theta_r \end{bmatrix}, \bar{I}_{r2} = \begin{bmatrix} v_r \\ \omega_r \end{bmatrix},$$
$$\bar{V}_{out} = \begin{bmatrix} v_{out} \\ \omega_{out} \end{bmatrix}, \bar{V}_{cmd} = \begin{bmatrix} v - rcmd \\ \omega - 1cmd \end{bmatrix}$$

First, let us define a positive-definite function

$$V_1(x_1, x_2) = x_1^2 + x_2^2 \tag{6}$$

Note that, it is the square of the distance between the mobile robot and the desired trajectory. Taking the derivative of V_1 along the trajectory yields

$$\dot{V}_1 = 2(x_2 u_1 + x_1 v_r \sin)x_0 \tag{7}$$

Choosing the saturation control law

$$u_1 = -sat_a(k_0 x_2) \tag{8}$$

where $k_0 > 0$ and $0 < a < v_{\max} - v_r$. Note that

$$|v| \le |u_1| + |v_r \cos x_0| < v_{\max} \tag{9}$$

satisfying the saturation constraint of the line velocitx. Using the equation, we can define following equation.

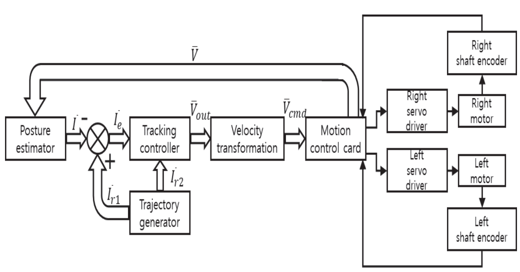

Fig. 2 The block diagram of the tracking control system of robot system

$$\dot{V}_1 = -2sat_a(k_0 x_2)x_2 + 2x_1 v_r \sin x_0 \tag{10}$$

Next, introduce a new variable

$$\bar{x}_0 = x_0 + \frac{\varepsilon h(t) x_1}{1 + V_1^{1/2}} \tag{11}$$

with $h(t) = 1 + \gamma\cos(t - t_0), 0 < \gamma < 1,$ and $0 < \varepsilon < \frac{1}{1+\gamma}$, where t_0 will be specified on the following theorem. Note that if $(\bar{x}_0, x_1, x_2)$ converges to zero, then the stability of (x_0, x_1, x_2) will be guaranteed[14]. With equation(12), system (6a) is transformed into

$$\dot{\bar{x}}_0 = \alpha(x_1, x_2, t)u_0 + \beta(x_0, x_1, x_2, t) \tag{12}$$

where

$$\alpha(x_1, x_2, t) = 1 - \frac{\varepsilon h x_2}{1 + V_1^{1/2}},$$

$$\beta(x_0, x_1, x_2, t) = \varepsilon\Big[\frac{\dot{h} x_1 + h w_r x_2 + h v_r \sin x_0}{1 + V_1^{1/2}} - \frac{h x_1}{(1 + V_1^{1/2})^2 V_1^{1/2}}(x_1 v_r \sin x_0 - sat(k_0 x_2)x_2)\Big]$$

It is easy to check that

$$0 < 1 - \varepsilon(1+\gamma) \le \alpha(x_1, x_2, t) < 2.$$

Choose the control law with constraint u_0 descrived as

$$u_0 = \frac{-\beta(x_0, x_1, x_2, y)}{\alpha(x_1, x_2, t)} - sat_b(k_1 \bar{x}_0) \tag{13}$$

with $k_1 > 0$ and $b > 0$. Then,

$$\dot{\bar{x}}_0 = -\alpha(x_1, x_2, t) sat_b(k_1 \bar{x}_0). \tag{14}$$

Note that $\lim_{\varepsilon \to 0} \frac{-\beta(\cdot)}{\alpha(\cdot)} = 0$. So, it is possible to choose a small $\varepsilon > 0$ and $b < 0$ such that $sup|u_0| < w_{\max} - sup|w_r(t)|$ [15].

Then $|w(t)| \leq |u_0| + |w_r| < w_{\max}$ satisfying the saturation constraint of the angular velocity. Define $V_2(\bar{x}_0)\bar{x}_0^2/2$. We then obtain

$$\dot{V}_2 = -\alpha(x_1, x_2, t) sat_b(k\bar{x}_0)\bar{x}_0$$
$$= \begin{cases} -\alpha(x_1, x_2, t) k_1 \bar{x}_0^2 & |k_1 \bar{x}_0| \leq b \\ -\alpha(x_1, x_2, t) b \bar{x}_0 & |k_1 \bar{x}_0| > b \end{cases}$$

This means that $\mathrm{Lim}_{t \to \infty} \bar{x}_0(t) = 0$ (by the Lyapunov stability theorem,

Now, we are in a position to present main results.

Theorem 1 Consider a simplified model (3) of mobile robots. Then the tracking problem with saturation constraint can be solved using control laws and (14) with $h(t) = 1 + \gamma\cos(t - t_0)$ where t_0 will be defined in the proof of theorem[16].

Proof: Due to limited space, the proof is omitted here. A similar proof can be found in the result of equation (8).

Remark: Although the LaSalle invariance principle can not be applied directly to non-autonomous systems. Its ideal can be applied here using some modification results, for details.

3.2 learning control scheme

The structure of the learning control system proposed in this study is shown in Fig. 7. The structure of the proposed control system consists of an upper, a lower, and an output unit. The top consists of a purgeizer and a calculation part of the suitability. The lower part consisted of an inference unit and an output unit[16].

The degree of conformity is determined using a backpropagation algorithm in the neural network for the error between the final output value and the target value.

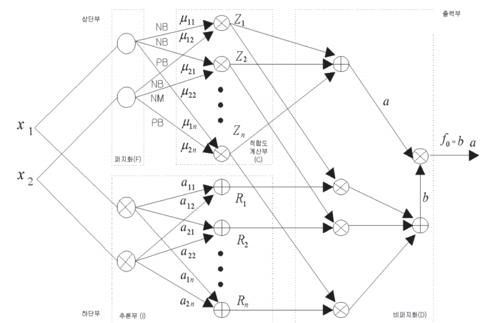

Fig. 3 Structure of learning control network

Using backpropagation learning algorithm, the adjustment amount of the center position for the belonging function is obtained[17].

$$\begin{aligned} \Delta c_{ij} &= -\alpha \cdot \frac{\partial \varepsilon}{\partial c_{ij}} \\ &= -\alpha \cdot \frac{\partial \varepsilon}{\partial f_0} \cdot \frac{\partial f_0}{\partial Z_j} \cdot \frac{\partial Z_j}{\partial c_{ij}} \\ &= \alpha \cdot (d - f_0) \cdot \frac{R_j - f_0}{\sum_{k=1}^{n} Z_k} \cdot Z_j \cdot \frac{(x_i - c_{ij})}{w_{ij}^2} \end{aligned}$$

The adjustment amount of the belonging function width is obtained using the same process.

$$\triangle w_{ij} = -\alpha \cdot \frac{\partial \varepsilon}{\partial w_{ij}} = -\alpha \cdot \frac{\partial \varepsilon}{\partial f_0} \cdot \frac{\partial f_0}{\partial Z_j} \cdot \frac{\partial Z_j}{\partial w_{ij}} = \alpha \cdot (d - f_0) \cdot \frac{R_j - f_0}{\sum_{k=1}^{n} Z_k} \cdot Z_j \cdot \frac{(x_i - c_{ij})^2}{w_{ij}^3}$$

The coefficient adjustment amount of the input/output linear relationship is expressed by the following equation.

$$\triangle a_{ij} = -\alpha \cdot \frac{\partial \varepsilon}{\partial a_{ij}} = -\alpha \cdot \frac{\partial \varepsilon}{\partial f_0} \cdot \frac{\partial f_0}{\partial R_j} \cdot \frac{\partial R_j}{\partial a_{ij}} = \alpha \cdot (d - f_0) \cdot \frac{Z_j}{\sum_{k=1}^{n} Z_k} \cdot x_i$$

Here, α represents the learning rate. If the output of the proposed control system is τ_n, the error equation is expressed by the following equation.

$$\ddot{e} + K_v \dot{e} + K_p e = \widehat{M}^{-1}(\triangle M \ddot{\theta} + \triangle N + F - \tau_n) \quad (15)$$

If the proposed controller uses the same learning signal as the target value, the error is asymptotically reduced.

4. Experimental Results

4.1 Simulation and results

The mobile robot developed in our study has two driving wheels and one casters for balance. The physical relation of experimental mobile robot and the mobile robot is briefly described here. Let v_L and v_R denote the velocities of the left wheel and the right wheel, respectively. In our case, the center of mass is equal to the center point between the left wheel and the right wheel.

Thus, its kinematic equation can be described as the equation (3) with $v = 0.5(v_L + v_R)$ and $w = (v_R - v_L)/E$ where E is the distance between the two driving wheels. So, the proposed controller can be applied to this case with $v_R = v + 0.5wE$ and $v_L = v - 0.5wE$.

The proposed algorithms have been verified by using computer simulation and practical experimental on an experimental mobile robot. The robot's hardware structure has two independent drive wheels and a free caster for balance The motion of the robot is controlled by changing the velocities of the left and right wheels. Two dedicated motion control chips HCTL-1100 from HP were employed for servo control of the two drive wheels. The integral velocity control mode was used in the experiments. The control computer only needs to send commands to the chips, which take care of the motor servo control. The position estimation of the robot is conducted using an odometer, which samples the left and right wheel velocities to calculate the current posture of the robot. The formula of this estimator is presented in as following equation

$$v = 0.5(v_L + v_R)$$
$$w = (v_R - v_L)/E$$
$$x_{new} = x_{old} + \triangle T \cdot v \cdot \cos(\theta_{old})$$
$$y_{new} = y_{old} + \triangle T \cdot v \cdot \sin(\theta_{old})$$
$$\theta_{new} = \theta_{old} + \triangle T \cdot w$$

where E is the distance between two drive wheels and T is the sampling period. The desired velocity calculated in the tracking algorithm is transferred into the left and right wheel velocities using

$$v_r = v_{out} + 0.5(L \cdot w_{out})$$
$$v_l = v_{out} - 0.5(L \cdot w_{out})$$

Two trajectories have been used to show the performance of the control law. Computer simulations were first conducted tor these trajectories and the parameters are determined by examining the desirable tracking performance. In the following the simulation and experimental results of tracking as well as docking performance are presented respectively for circular and parallel parking trajectories. Experimental results corresponding to the same conditions are also shown in these plots for comparison. These results demonstrate the ability of the proposed controllers in producing nice convergence behavior.

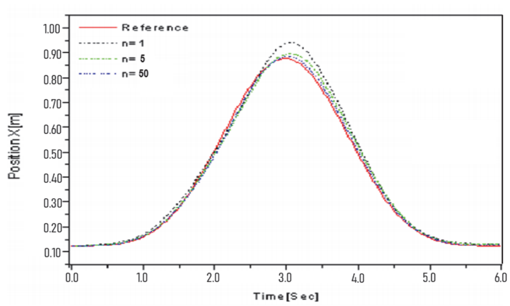

Fig. 4 Control result of position x for iteration number (n=5)

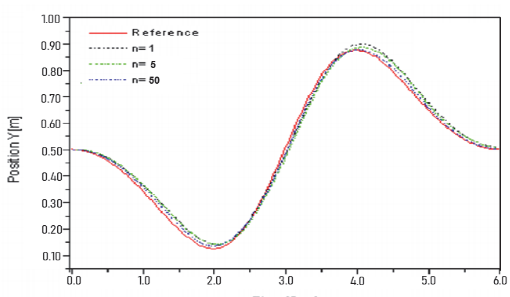

Fig. 5 Control result of position y for iteration number (n=20)

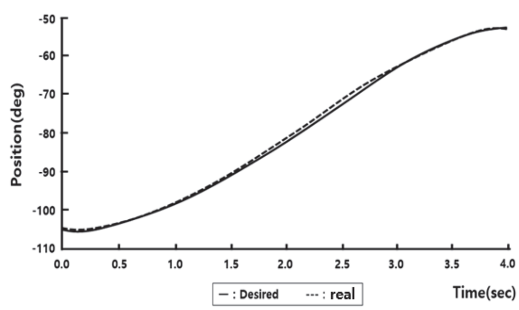

Fig. 6 The tracking control result of angular position of robot system(n=10)

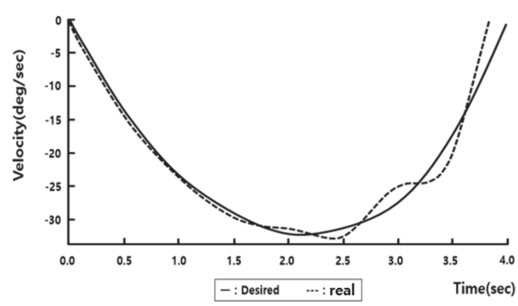

Fig. 7 The velocity control result of robot system(n=5)

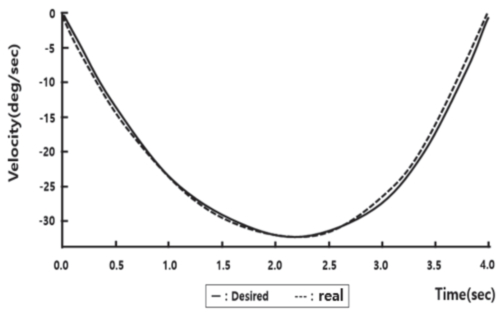

Fig. 8 The velocity control result of robot system(n=20)

Fig. 4 shows Control result of position x of robot system for iteration number Fig. 5 shows Control result of position y of robot system for iteration number Fig. 4 shows the result of angular position control for robot system when iterative number is 10. And Fig. 7 shows the result of velocity control of robot system when iterative number is 5. Fig. 8 shows the velocity control result of robot system when iterative number is 20.

4.2 Experiment and results

In this study, the reliability of control performance has beeen illustrated by experiment for mobile robot with two driving wheel and cast.

Fig. 9 represents the experiment scene for performance test of trajectory tracking control of mobile robot. Fig. 10 shows the tracking control result of desired trajectory when iteration numbe is fifty. And Fig. 11 shows the tracking control result of desired trajectory when iteration number is hundred.

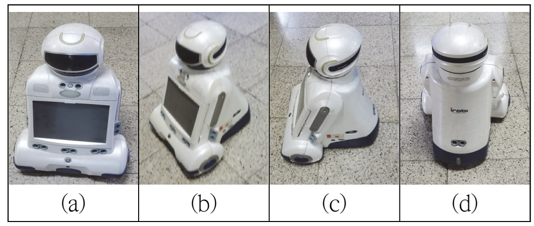

Fig. 9 The experiment scene of robot systme for trajectory tracking

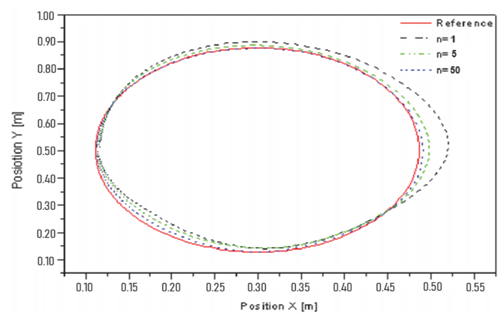

Fig. 10 Tracking trajectory for iteration numbe(n=50)

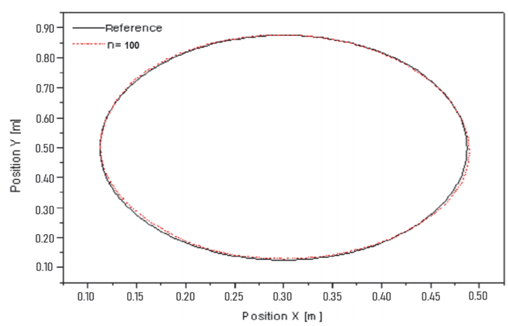

Fig. 11 Tracking trajectory by iteration number(n=100)

5. Conclusion

This study proposed a new approach for intelligent motion control of mobile robot based on iterative learning for smart factory

In this research, it is the most important to impliment the real time iterative learning control of a mobile robot by back properpagation algorithm based on multi-layer neural network. The reliability of control algorithm was varified by simulation and experiments. From performance test, it had been illustrated to be effected by the friction of wheels, variation of system parameters, and external disturbance. In the future, we would like to illustrate the reliability of intelligent working control of the mobile robot in external field.

References

[1] Hee-jin Kim, Guen-Han Dong, Dong-Ho Kim, Gi-Won Jang, Sung-Hyun Han, "A Study on Track Record and Trajectory Control of Articulated Robot, KSIC Vol. 25, No. 2, pp.149-161, 2020.

[2] C. de Wit Canudas. B Siciliano, and G. Bastin. eds Theory of Robot Control, Springei-Verlag. London. 1996.

[3] C C Chang and K. T. Song. "Environment prediction lor a mobile robot in a dynamic environment" in IEEE Trans, on Robotics and Automation. Vol. 13, No. 6, pp.862-872. 1997.

[4] P Fiorini and Z. Shiller. "Motion planning in dynamic environments using velocity obstacles.“ in the Int. J. of Robotics Research, Vol. 17. No. 7, pp.760-772, 1998.

[5] Y. J. Kanayama, Y.Kimura, F. Miyazaki, and T.noguchi, "A stable tracking control scheme for an autonomous mobile robot." in Proc. IEEE hit Conf, on Robotics and Automation. pp.384-389, 1990.

[6] J. P Laumond, P. E. Jacobs, M. Taix. and R. M. Murray. "A motion planner tor nonholonomic mobile robots" in IEEE Triins on Robotics and Automation, Vol 10, No. 5, pp.577-593, 1994.

[7] V. C. Lee, C. H. Lee. and C. C. Teng, "Tracking control of mobile robots using backstepping technique," 5th International Conference on Control. Automation, Robotics and Vision, pp.1715-1719. Dec. 8-11, 1998, Mandarin Singapore. Singapore.

[8] R. T. N'Closkey. and R. M. Murray, "Exponential stabilization of drift less control systems using homogeneous ieedback." in IEEE Trans. Autnmatic Control 42 No.5, pp. 614-628, 1997.

[9] R. T. M'Closkey and R. M Murray, "Exponential stabilization of nonlinear driftless control systems via time-varying homogeneous feedback," in IEEE Conf. On Decision and Control. Lake Buena Vista, pp.1317-1322, 1994.

[10] R. M. Murrax. G. Walsh, and S. S. Sastry, "Stabilization and tracking for nonholonomic control systems using time-varxing state feedback." in IFAC Nonlinear Control Systems Design. Bordeaux, ed. M. Fliess. pp.109-114. 1992.

[11] R. M. Murray and S. S. Sastry, "Nonholonomic motion planning: steering using sinusoids," in IEEE Trans on Automatic Control, Vol. 38, No. 5, pp.700-716. 1993.

[12] W. Oelen and J. van Amerongen. "Robust tracking control of two-degree-freedom mobile robots." in Control Engng Practice 2. pp.333-340, 1994.

[13] 김희진, 김상현, 장기원, 김두범, 동근한, 한성현, "스마트 팩토리를 위한 로봇 모니터링 시스템 시뮬레이터 개발에 관한 연구", 한국산업융합학회논문집 vol.22, No.5, pp.561-574, 2015.

[14] Hee-jin Kim, Dong-Ho Kim, Kum-Jun Jung, Sung-Hyun Han, "A Study on Perfomance Analysis of Articulated Robot System for

Smart Factory Based on Monitoring Simulator", KSIC vol.23, No.6, pp.889-896, 2020.

[15] 정금준, 김동호, 김희진, 장기원, 한성현, "스마트 팩토리 실현을 위한 뉴럴네트워크 기반 이중 아암을 갖는 제조용 로봇의 지능제어에 관한 연구", 한국산업융합학회논문집 vol.24, No.3, pp. 351-362, 2021.

[16] Hee-jin Kim, Dong-Ho Kim, Gi-Won Jang, Byeong-Hwa Gu, Sung-Hyun Han, "A Study on a New Approach to Robust Control and Torque Control Response Analysis of Manufacturing robot Based on Monitoring Simulator for Smart Factory", KSIC vol.24, No.4, pp.397-409, 2021

[17] Hee-jin Kim, Dong-Ho Kim, Sung-Hyun Han "A Study on Fuzzy Logic Based intelligent Control of Robot System to lmprove the Work Efficiency for Smart Factory", KSIC vol.24, No.6, pp.645-658, 2021.

(Manuscript received June 29, 2022;
revised August 02, 2022; accepted August 10, 2022)