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Delay Compensation on Fuzzy Trajectory Tracking Control of Omni-Directional Mobile Robots

A. Sheikhlar[1], M. Zarghami[2], A. Fakharian[3*] and M. B. Menhaj[4]

1-. MSc Student, Department of Electrical, Biomedical and Mechatronic Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran.
2- MSc Student, Young Researchers and Elite Club, Qazvin Branch, Islamic Azad University, Qazvin, Iran.
3- Assistant Professor, Department of Electrical, Biomedical and Mechatronic Engineering, Qazvin Branch, Islamic Azad University, Qazvin, Iran.
4- Professor, Electrical Engineering Department, Amirkabir University of Technology, Tehran, Iran.

ABSTRACT

This paper presents a delay compensator fuzzy control for trajectory tracking of omni-directional mobile robots. Fuzzy logic control (FLC) of the robots is a suitable strategy for dealing with model uncertainties, nonlinearities and disturbances. On the other hand, in many robotic applications such as mobile robots, delay phenomenon is able to substantially deteriorate the behavior of system's performance if not considered in the controller design. In this work, a delay compensator strategy is employed in order to eliminate the influence of dead time problem. On the other hand, a discrete-time kinematic model is presented for high level control of SSL soccer robots. Also, the model uncertainties are considered as multiplicative parameters and external random disturbances are noticed as additive parameters. The simulation experiments as well as real system experiments demonstrate that the proposed method handles both constant time delay and uncertainties with a small tracking error in comparison with pure fuzzy control.

KEYWORDS

Delay Compensation, Fuzzy Control, Trajectory Tracking, Omni-Directional Mobile Robot, Soccer Robot.

* Corresponding Author, Email: Ahmad.fakhrian@qiau.ac.ir

1- INTRODUCTION

Omni-directional wheeled robot is a type of mobile robots which is used in many studies because of its maneuverability, remarkable accuracy and swiftness. Omni-directional wheels of this robot, allow it to move simultaneously and independently along different paths. The substantial drawbacks of mobile robot's motion control can be classified in three categories: point regulation, path following and trajectory tracking [1]. The trajectory tracking is a fundamental element of navigation procedure in omni-directional mobile robots. In this context, the robot utilizes the information of state and environment for planning its movement ahead. The reference trajectory that is already generated is then presented to the trajectory tracker to perform actual movements. The purpose of tracker is to successfully navigate the robot on desired trajectory, by considering the model uncertainties and motion disturbances.

The research field of the mobile robot's trajectory tracking possesses a huge quantity of literature ranging from classical control methods [2, 3], to nonlinear control strategies [4, 5] and automatic control methodologies [6-9]. Nowadays, trajectory tracking control of autonomous mobile robots in presence of unknown dynamics and uncertainties is became an energetic research field [10-12]. Many studies with pure constraints assume nominal kinematics or dynamics [13, 14], however obtaining accurate kinematics and dynamics is a hard work and actual mobile robot may be influenced by many uncertainties. Consequently, a reasonable way is choosing a technique that is not dependant on precise mathematical model of the robot. Fuzzy logic control (FLC) seems to be a suitable solution for this situation and it shows better consequences when it utilizes for controlling the systems with nonlinearities and/or uncertainties such as omni-directional soccer robots. Therefore, today's widespread study efforts on fuzzy controllers in trajectory tracking of mobile robots in the presence of uncertainties have been appeared [15-17]. Nevertheless, the compensation of time delay in partially uncertain robots seems to be out of attention in recent studies. The delay phenomenon usually occurs in dynamic systems and it is able to enfeeble the system's performance if not considered in the controller design. Also, delay systems control is an important challenge in many robotic platforms. In addition, without consideration of mathematical problems in dynamic modeling of plant, system's delay causes many challenging control troubles. In continues delay systems, discrete control should face even more problems due to the sampling. Consequently, using an innovative strategy for compensating the dead-time in uncertain systems such as soccer robots can be a suitable solution. Although model predictive control techniques are utilized as delay compensation strategies [18], but their highly dependence on precise mathematical model of the controlled object makes them infeasible in uncertain systems.

From the above Considerations, we can conclude that the FLC is capable to deal with model uncertainties of soccer robots; while delay compensation strategy can cope with the dead time of wireless communication between Artificial intelligence (AI) system and the robots. The combination of these two strategies presents an efficient approach in tracking control of autonomous mobile robots.

2- PROBLEM FORMULATION

This part of paper explains specifications of the SSL robot as a four wheeled omni-directional fast soccer robot and its kinematic models in global and moving coordinates. The SSL robot is equipped with four Maxon brushless motors (50 Watts) and each motor contains a mechanically driven shaft encoder and three hall sensors. Four PWM voltages generated with central ARM microcontroller are as input signals to control the position and orientation of robot. Fig. 1(a) demonstrates the appearance of the SSL robot.

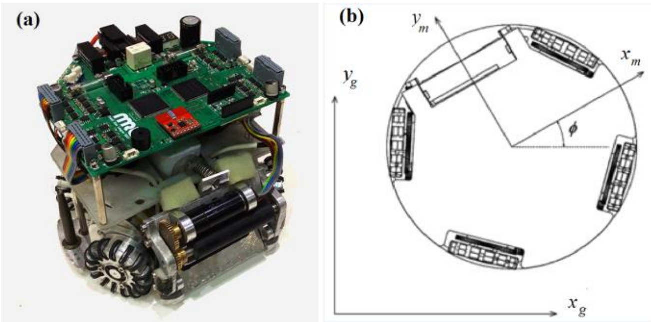

Fig. 1 (a). MRL SSL robot. (b) Mobile and world coordinates.

Robot teams in SSL robocup, receive the information of the robots positions from two cameras called vision system that is installed several meters above the soccer field which has a LAN connection with the artificial intelligence (AI) system. The SSL has utilized a shared vision system called SSL-vision since 2010 [19]. The most important fountainhead of feedback in the whole architecture is SSL-Vision. There is a wireless connection between robots and the AI system. The control commands are sent with an almost constant delay from the AI to the robots in soccer field. Fig. 2 shows the data flow of a SSL match.

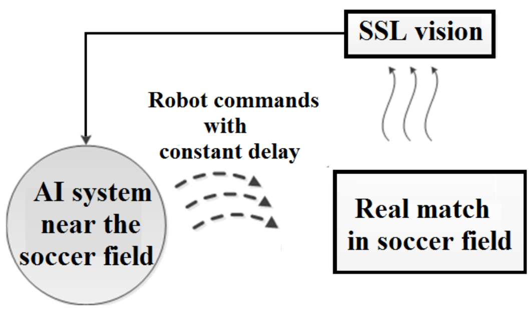

Fig. 2. Data flow of a SSL match.

The closed loop system of many soccer robot platforms has an almost similar structure as depicted in Fig. 3. For instance, in SSL robots, high level controller creates the robot's velocity in world coordinates (or global coordinates). The wireless commands that are sent form artificial intelligence to the robots in soccer field contain an almost constant dead time. In the subsequent stage, the control signal is converted from world frame coordinates to moving frame coordinates. After that, the reference velocity of actuators is generated via robot's inverse kinematics. As we focused on SSL robots that have four wheels, four PID controllers are utilized for low level control task and changing each motor's speed. On the other side, the position and velocity of the robot are measured using vision system and encoders. Since the measured data of vision system has high frequency noise, a typical filter is applied to deal with this issue. In Fig. 3, U_w represents the desired velocity vector in world coordinates, U_m is the velocity in mobile coordinates.

The SSL robot has two coordinates: moving and world coordinates. The position and orientation of robot depicted in Fig. 3 in both coordinates are:

$$\begin{cases} X_m = [x_m \quad y_m \quad \varphi]^T \\ X_w = [x_w \quad y_w \quad \varphi]^T \end{cases} \tag{1}$$

Rotation matrix ${}^g_bR$ is used to convert the moving frame coordinates to world frame coordinates and it is represented as following:

$${}^g_bR = \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Equation (3) shows the velocity vector in global coordinates. Taking time derivative of the robot position vector results this expression. The robots velocity vector which related to the wheel geometry and angular velocity in the word coordinates expressed as:

$$\dot{X}_w = {}^g_bR\dot{X}_m = {}^g_bR(B^T)^{-1} r\omega_L \tag{3}$$

And Geometrical matrix B is:

$$B = \begin{bmatrix} -\sin\theta_1 & -\sin\theta_2 & -\sin\theta_3 & -\sin\theta_4 \\ \cos\theta_1 & \cos\theta_2 & \cos\theta_3 & \cos\theta_4 \\ l & l & l & l \end{bmatrix} \tag{4}$$

$\theta_i, \quad i = 1,2,3,4$ is angle of wheels respect to moving coordinates. Equation (3) and (4) demonstrates the kinematics of a four wheeled omni-directional robot in moving coordinates. Angular velocity matrix of the wheels ω_L elements, wheel radius r and robot geometry are used in calculation of the robot's velocity.

In the current research, a linear kinematic model is sufficient for high level control task and it guarantees a reasonable response. The linear kinematic equations in world coordinates can be written as follows.

$$\begin{cases} \dot{x}_w(t) = \alpha_1 v_x{}^c(t - t_d) \\ \dot{y}_w(t) = \alpha_2 v_y{}^c(t - t_d) \\ \dot{\phi}_w(t) = \alpha_3 \omega^c(t - t_d) \end{cases} \tag{5}$$

or, in a more compact formulation:

$$\dot{X}_w = f(\mathrm{U}, \alpha) \tag{6}$$

where X_w represents the state vector and as shown in (1), it describes the position and orientation of the robot in world coordinates and $U = [v_x^c \quad v_y^c \quad \omega^c]^T$ shows the command velocity vector (input velocity) in continuous mode. We assume that the input velocity in specific direction such as x, has a linear relation with its relevant position's derivative in global coordinates. Also, the constant time input delay is assumed t_d. It is necessary to mention that the interaction between three directions is considered by the uncertain parameter $\alpha_i \quad i = 1,2,3$. After, applying the Euler's approximation to (6), the robot is modeled in discrete mode by following equations

$$\begin{cases} x\ (\mathrm{k}+1) = x\ (\mathrm{k}) + \alpha_1 v_x{}^c(\mathrm{k} - k_d) \\ y\ (\mathrm{k}+1) = y\ (\mathrm{k}) + \alpha_2 v_y{}^c(\mathrm{k} - k_d). \\ \phi\ (\mathrm{k}+1) = \phi\ (\mathrm{k}) + \alpha_3 \omega^c(\mathrm{k} - k_d) \end{cases} \tag{7}$$

Here α_1, α_2 and α_3 are uncertain parameters and they are called motor correction factors. These parameters can greatly affect the performance of robots control system. The nominal value of each of them is $1/60$ while experimental results show that their real value usually changes in interval $[0.7/60 \quad 1/60]$ during the motion of robot. The alterations of α depends on the motors heat, stick of soccer field carpet's lint to the robot wheels, friction of the wheels and many unknown dynamics that cannot be modeled precisely. The value of $\alpha_i \quad i = 1,2,3$ can be calculated by following equation in each sampling time *k*:

$$\alpha_i(k) = \frac{1}{T} \sum_{j=k-n_0}^{k} \frac{X_r(j)}{X_d(j)} \quad i = 1,2,3 \tag{8}$$

where X_d and X_r are desired and real position (and orientation) of the robot respectively. Each i presents the corresponding direction in world frame coordinate.

The speed and acceleration of an omni-directional robot at each point on its trajectory should be within permissible bounds. In [20], velocity and acceleration filters have been made for the robot and it normalize their components that leads to practical maximum translational velocity and acceleration as $V_{\max} = 3.159 m/s$ and $a_{\max} = 0.826 m/s^2$.

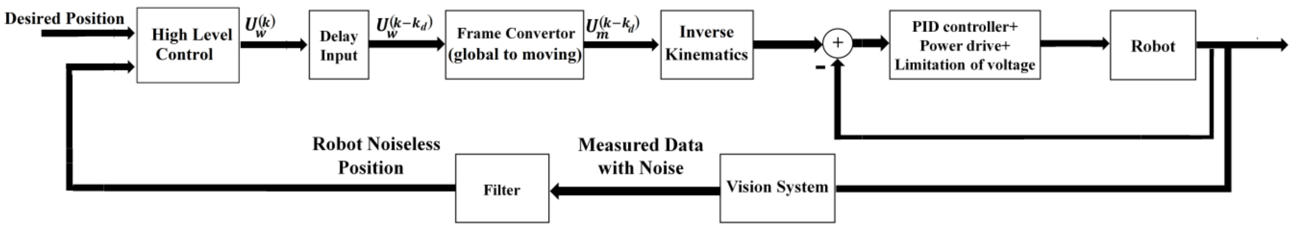

Fig.3. Closed loop system's block diagram.

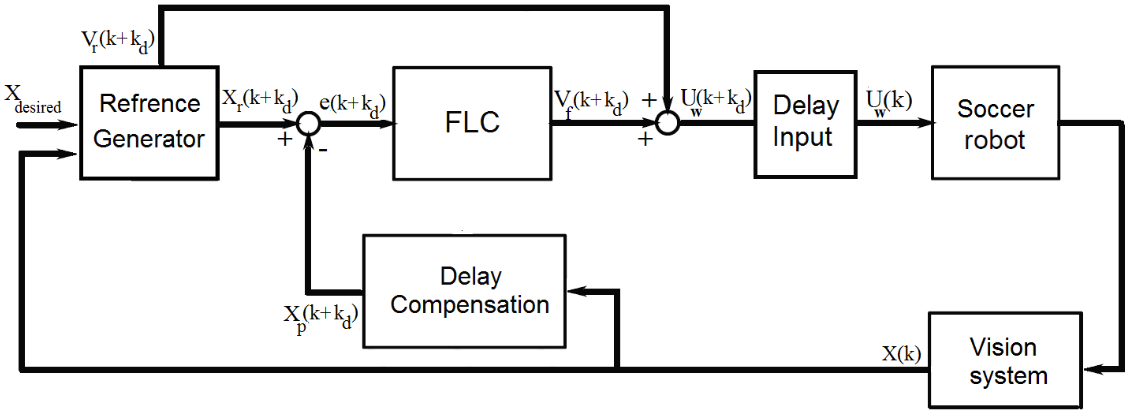

Fig. 4. High level control structure.

3- METHODOLOGY

As demonstrated in Fig. 4, the proposed high level controller structure is presented. First of all, a set point $X_{desired}$ which is the target of the omni-directional mobile robot is given. A reference trajectory should be selected $X_p(k+k_d)$ using current position $X(k)$. Subsequently, the FLC produces velocity V_f in x and y direction according to error $e(k+k_d)$ between the subsequent reference position and the predicted position of the robot. Finally, control signal $U_w(k+k_d)$ in world coordinates is generated using the FLC's output and the reference velocity. As mentioned, the command velocity (control signal) is sent to robot with a constant time delay t_d .

A. REFERENCE GENERATOR

The performance of trajectory tracking in omni-directional soccer robots is mostly associated with the calculation of appropriate reference trajectory. This concept is then enlarged when the hardest part is to find the suitable reference velocity along x and y axis according to the robot's current position. The well-worth mentioning fact is that the produced velocity along x and y direction are not the same because of the robot's structure.

In this paper, the reference parameters are calculated via an approach presented in [20]. On this case, the robots acceleration and the time arrival to target point is mainly based on set point and the robot's current position $X(k)$. The subsequent reference position $X_r(k+k_d)$ is specified according to these assumptions. Also, the delay compensation algorithm is able to predict next position

focused and discussed in every possible condition. This can leads to provide an ideal trajectory for real robot. In this research, due to the presence of several types of noises in robot structure, the reference parameters are iteratively updated on each sample time which makes the robot to move on the path more smoothly.

B. DELAY COMPENSATOR

The compensation of the delay in practical applications is become an interesting concept in control literature. This consideration is made the presented control structure more robust.

Furthermore, it is able to handle dead time drawback in plants and it can eliminates the influence of the dead time by predicting the future sequence of the system's output. This work uses a linearized mathematical model of robot presented in (7) for the mentioned purpose. Then, this simplified linear model is utilized for predicting the next position of robot.

In the case of motion control, the term *e* is defined as the error between the reference position and the predicted position for a given, and it is expressed as:

$$e_x(k) = x_r(k) - x_p(k)$$
$$e_y(k) = y_r(k) - y_p(k) \tag{9}$$

Where x_p and y_p are robot's predicted position in two directions; x_r and y_r are robot's pre-defined components of reference trajectory at time step k and they are calculated in advance. Also, x_p and y_p are formulated as:

$$x_p(k) = x(k) + x_{comp}(k)$$
$$y_p(k) = y(k) + y_{comp}(\text{k}). \tag{10}$$

Here, x_{comp} and y_{comp} compensate the effect of dead-time. By proposing this approach, a considerable development is occurred in output of system. Now, x_{comp} and y_{comp} can be shown as below:

$$x_{comp}(k) = \sum_{i=k-k_d}^{k} v_{x_i} \alpha_x T$$
$$y_{comp}(k) = \sum_{i=k-k_d}^{k} v_{y_i} \alpha_y T \tag{11}$$

Where T is the sampling time which is introduced by system's application. The v_{x_i} and v_{y_i} are input parameters of system that represent the robot's command velocities in each direction x and y.

After evaluating (9), the estimated error of robot's position will be carried out in the FLC which has to obtain the optimum input for next time step. The brief introduction of fuzzy algorithm will be presented in the following section.

C. FUZZY LOGIC CONTROL

In this research, the FLC is employed to achieve the position control of four wheeled omni-directional mobile robot. The e_x and e_y are two inputs to the FLC which are the errors between the reference value and predicted value of robot's position in x and y direction. The outputs are v_x and v_y, which are the command velocities for positioning of the robot in desired trajectory. Since we have focused on position control (not orientation control), the errors of x and y direction of the robot's position are utilized. The rules and ranges of the fuzzy controller are designed based on some constraints of the robot's motion such as the velocity limitation. We have used 25 rules in fuzzy system. This number of fuzzy rules guarantees desired performance and also a sensible computational cost. In design of the FLC, for the input and output variables (e_x, e_y, v_x and v_y), five membership functions NB, NS, ZO, PS, and PB are employed. They represent negative big (NB), negative small (NS), zero (ZO), positive small (PS) and positive big (PB). Five triangle membership functions are utilized for each input and output variable as demonstrated in Fig. 5 and Fig. 6.

Since it is assumed that the robot doesn't deviate from the reference trajectory more than ε meter, the input fuzzy range is decided: e_x and $e_y \in [-\varepsilon, \varepsilon]$ *(m)*. Also, output fuzzy range is decided by considering the robot's maximum velocity: v_x and $v_y \in [-\delta, \delta]$ *(m/s)*. These small ranges of fuzzy subsets are able to make the FLC sensitive to small alterations in robot's location.

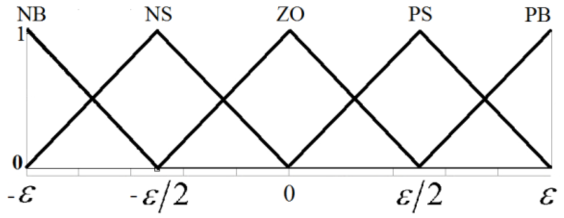

Fig. 5. Membership function of input variables e_x and e_y

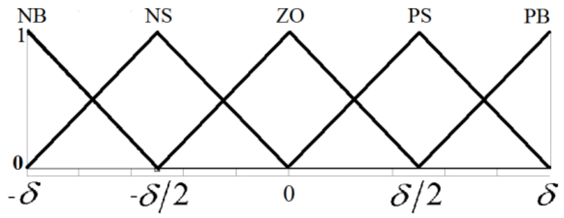

Fig. 6. Membership function of output variables v_x & v_y

In this step, 25 fuzzy rules are designed based on a simple concept: when the robot deviates from the reference trajectory in a direction, it is the FLC's task to give an appropriate velocity to bring the robot back to desired path in the same direction. Fuzzy rules of the FLC are proposed as follows.

TABLE 1. FUZZY RULES FOR v_x

v_x		e_x				
		NB	**NS**	**ZO**	**PS**	**PB**
e_y	**NB**	NB	NS	ZO	PS	PB
	NS	NB	NS	ZO	PS	PB
	ZO	NB	NS	ZO	PS	*PB*
	NS	NB	NS	ZO	PS	PB
	NB	NB	NS	ZO	*PS*	PB

TABLE 2. FUZZY RULES FOR v_y

v_y		e_x				
		NB	**NS**	**ZO**	**NS**	**NB**
e_y	**NB**	NB	NB	NB	NB	NB
	NS	NS	NS	NS	NS	NS
	ZO	ZO	ZO	ZO	ZO	*ZO*
	PS	PS	PS	PS	PS	PS
	PB	PB	PB	PB	*PB*	PB

For instance, the rules are exerted as: if e_x is NB and e_y is PS, then v_x is NB and v_y is PS. In the proposed FLC, the Mamdani's Min-Max operator is implemented to perform inference between the input and output variables. Also, the center of gravity method is utilized to perform defuzzification task and get the crisp values.

4- RESULTS

In this section, two sets of simulation results are presented to show the effectiveness of presented control scheme. The proposed approach is called delay compensator FLC tracking method and it is compared to the non-compensated fuzzy control to show the influence of the delay compensation strategy in trajectory tracking of omni-directional soccer robots. This research is conducted with the aim of high level kinematics linearization and employing an almost model-free method for control of the above-mentioned robots. Consequently, the simulation results of the presented control method have been provided for a rectangular trajectory motion tracking. The position of robot is controlled and regulated by the mentioned delay compensator fuzzy technique as a high-level controller and leads to passable tracking error compared to the pure fuzzy method. Also, in order to demonstrate the robustness of the presented tracking control, a separated set of simulations with respect to a stochastic disturbance have been performed.

In this work, the sampling time of measurement system are selected based on SSL vision package's frame period: $T = fp = 1/60\sec$.Also, the time delay of wireless communication between the AI and robot is considered: $t_d = 0.1\sec = 6fp$. All time-based figures in the current section are plotted based on SSL vision's frame period *(fp)*. Also, the values of fuzzy range parameters are selected according to maximum velocity and maximum acceleration of the robot. In addition, it is assumed that the error between the reference and the predicted position is smaller than 10 centimeters. Thus, the ranges are $e_x, e_y \in [-0.1, 0.1]$ *(m)* and $v_x, v_y \in [-1,1]$ *(m/s)*.

Fig. 7 demonstrates the path tracking behavior of the omni-directional SSL robot for the pure FLC and delay compensator FLC (comp-FLC) methods and as it is clear, the proposed delay compensator FLC presents more accurate tracking compared to the FLC approach. As shown in Fig. 8, the alterations in velocity profile curves are related to adapting the SSL robot with path's characteristics with respect to the trajectory's geometrical specifications. Fig. 9 and table 3 show that the maximum tracking error of the horizontal and vertical movements are reduced 35% and 49% respectively for the delay compensator FLC in comparison with pure FLC.

Fig. 10 demonstrates the path tracking performance of the SSL robot in presence of random disturbance as an additive uncertainty. To examine the robustness of the presented delay compensator FLC (comp-FLC), the right side of (7) has been added to a randomly distributed noise with amplitude 0.1.

As it is clear, the presented strategy is able to reduce the deviation of robot from the desired path. Fig. 11 shows the alterations of control signal in a noise-polluted environment.

Finally, Fig. 12 and table 4 exhibit that the maximum trajectory tracking errors of the x and y axis movements in the presence of randomly distributed noise are reduced 34% and 60% respectively for the delay compensator FLC in comparison with pure FLC.

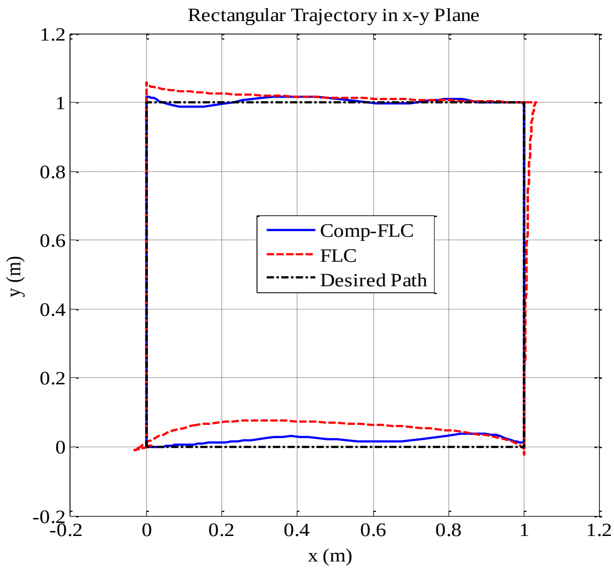

Fig. 7. Rectangular trajectory-following behavior for robot's translational movement for FLC and delay compensator FLC approaches

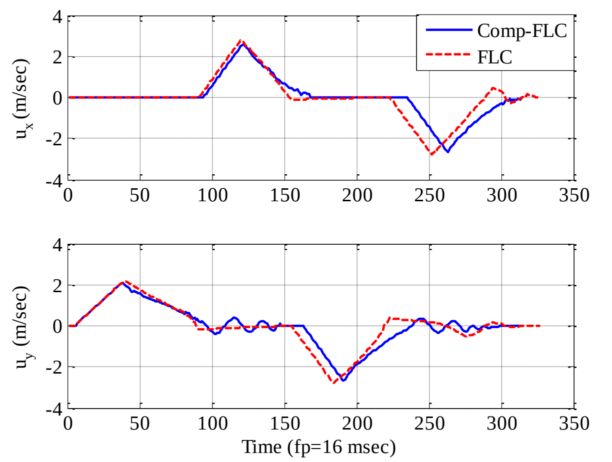

Fig. 8. FLC and delay compensator FLC controllers output

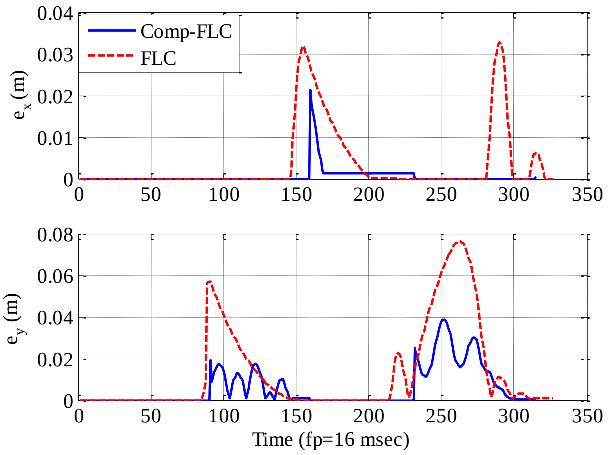

Fig. 9. Absolute of position error for FLC and delay compensator FLC

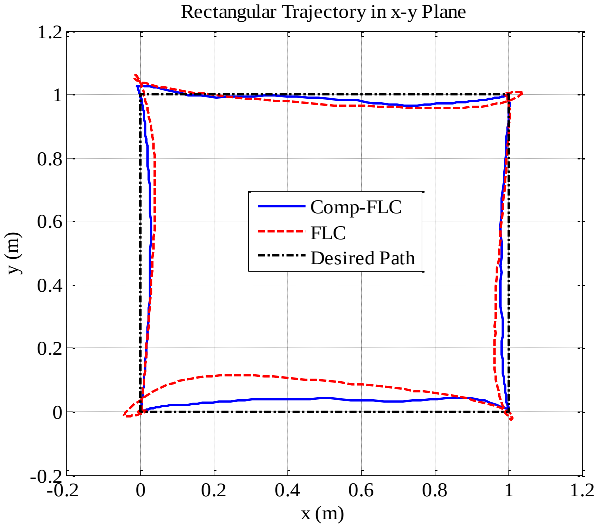

Fig. 10. Rectangular trajectory-following behavior for robot's translational movement in the presence of randomly distributed disturbance

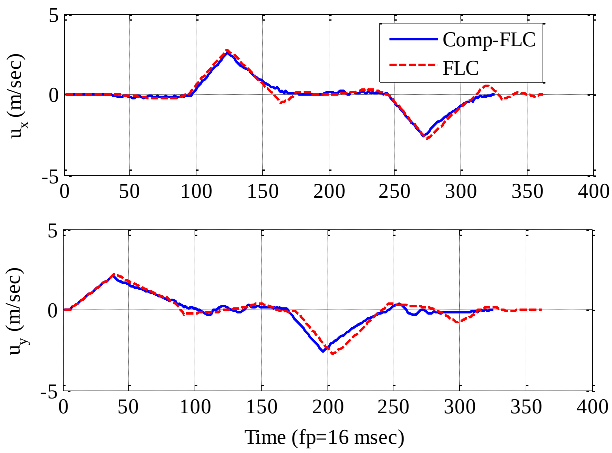

Fig. 11. FLC and delay compensator FLC controllers output in the presence of randomly distributed disturbance

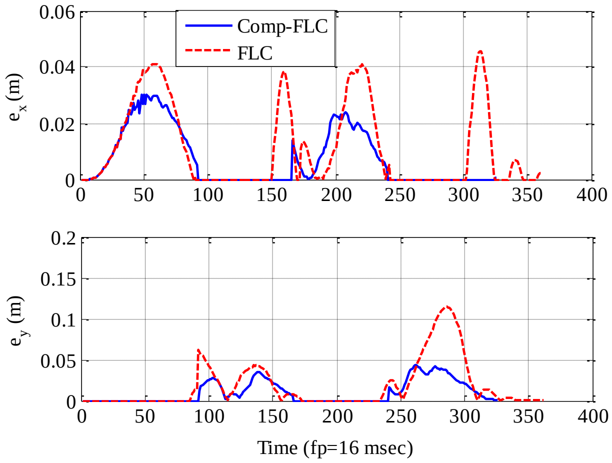

Fig. 12. Absolute of position error for FLC and delay compensator FLC in presence of randomly distributed disturbance

TABLE 3. POSITION ERROR ANALYZE

	Maximum error	Mean error
Delay compensator FLC (x direction)	2.124 cm	0.055 cm
FLC (x direction)	3.286 cm	0.36 cm
Delay compensator FLC (y direction)	3.864 cm	0.57 cm
FLC (y direction)	7.611 cm	1.33 cm

TABLE 4. POSITION ERROR ANALYZE IN PRESENCE OF RANDOM NOISE

	Maximum error	Mean error
Delay compensator FLC (x direction)	3.007 cm	0.74 cm
FLC (x direction)	4.557 cm	1.13 cm
Delay compensator FLC (y direction)	4.111 cm	0.10 cm
FLC (y direction)	10.154 cm	1.75 cm

5- CONCLUSION

In this paper, a delay compensator fuzzy trajectory tracking control is applied to the four wheeled omni-directional soccer robot to realize delay drawback. Also, the proposed method is able to deal with uncertainties of robot's model and environment disturbances. Simulation tests are performed to examine the effectiveness of this controller. The results demonstrate that the delay compensator fuzzy controller follows a rectangular trajectory with high accuracy in comparison with pure fuzzy controller. Also, the presented control has a robust performance in presence of randomly distributed disturbances.

REFERENCES

[1] L. Vachhani, A. D. Mahindrakar, and K. Sridharan. "Mobile robot navigation through a hardware-efficient implementation for control-

law-based construction of generalized voronoi diagram." Mechatronics, IEEE/ASME Transactions on 16.6 (2011): 1083-1095.

[2] Altafini, Claudio. "A path-tracking criterion for an LHD articulated vehicle."The International Journal of Robotics Research 18.5 (1999): 435-441.

[3] A. KAMAGA, and Ahmed Rachid. "A simple path tracking controller for car-like mobile robots." Choice 1 (1997): 2.

[4] Altafini, Claudio. "Following a path of varying curvature as an output regulation problem." (2002).

[5] Wit, Jeff, Carl D. Crane, and David Armstrong. "Autonomous ground vehicle path tracking." Journal of Robotic Systems 21.8 (2004): 439-449.

[6] Antonelli, Gianluca, Stefano Chiaverini, and Giuseppe Fusco. "A fuzzy-logic-based approach for mobile robot path tracking." Fuzzy Systems, IEEE Transactions on 15.2 (2007): 211-221.

[7] Omid Mohareri, Rached Dhaouadi, and Ahmad B. Rad. "Indirect adaptive tracking control of a nonholonomic mobile robot via neural networks."Neurocomputing 88 (2012): 54-66.

[8] Yang, Simon X., et al. "A bioinspired neurodynamics-based approach to tracking control of mobile robots." Industrial Electronics, IEEE Transactions on 59.8 (2012): 3211-3220.

[9] Bingül, Zafer, and Oğuzhan Karahan. "A Fuzzy Logic Controller tuned with PSO for 2 DOF robot trajectory control." Expert Systems with Applications 38.1 (2011): 1017-1031.

[10] Park, Bong Seok, et al. "A simple adaptive control approach for trajectory tracking of electrically driven nonholonomic mobile robots." Control Systems Technology, IEEE Transactions on 18.5 (2010): 1199-1206.

[11] K. Shojaei, and A. M. Shahri. "Output feedback tracking control of uncertain non-holonomic wheeled mobile robots: a dynamic surface control approach."Control Theory & Applications, IET 6.2 (2012): 216-228.

[12] Zhong, Guoliang, et al. "Trajectory tracking of wheeled mobile robot with a manipulator considering dynamic interaction and modeling uncertainty."Intelligent Robotics and Applications. Springer Berlin Heidelberg, 2012. 366-375.

[13] C. Canudas de Wit and O. J. Sordalen, “Exponential stabilization of mobile robot with nonholonomic constraints,” IEEE Trans. Autom. Control, vol. 37, no. 11, pp. 1791–1797, Nov. 1992.

[14] C. Samson, “Control of chained system application to path following and time-varying point-stabilization of mobile robots,” IEEE Trans. Autom. Control, vol. 40, no. 1, pp. 64–77, Jan. 1995.

[15] Zhong, Guoliang, et al. "Trajectory tracking of wheeled mobile robot with a manipulator considering dynamic interaction and modeling uncertainty."Intelligent Robotics and Applications. Springer Berlin Heidelberg, 2012. 366-375.

[16] Chwa, Dongkyoung. "Fuzzy adaptive tracking control of wheeled mobile robots with state-dependent kinematic and dynamic disturbances." Fuzzy Systems, IEEE Transactions on 20.3 (2012): 587-593.

[17] Jafar Keighobadi, and Mohammad B. Menhaj. "From nonlinear to fuzzy approaches in trajectory tracking control of wheeled mobile robots." Asian Journal of Control 14.4 (2012): 960-973.

[18] Cortes, Patricio, et al. "Delay compensation in model predictive current control of a three-phase inverter." Industrial Electronics, IEEE Transactions on 59.2 (2012): 1323-1325.

[19] S. Zickler, T. Laue, O. Birbach, M. Wongphati, and M. Veloso, “SSLVision: The Shared Vision System for the RoboCup Small Size League”, RoboCup 2009: Robot Soccer World Cup XIII, vol. 5949, pp. 425–436, 2009.

[20] E. Hashemi, M. Ghaffari Jadidi, O. Bakhshandeh, Trajectory planning optimization with dynamic modeling of four wheeled omni-directional mobile robots, in: Proc. of IEEE Int. Conf. on Computational Intelligence in Robotics and Automation, December 2009, pp. 272–277.

[21] Purwin, Oliver, and Raffaello D’Andrea. "Trajectory generation and control for four wheeled omnidirectional vehicles." Robotics and Autonomous Systems54.1 (2006): 13-22.