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Fuzzy control of omnidirectional robot

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Abstract

This paper presents the design of fuzzy control system for an omnidirectional robot. The control structure of omnidirectional robot was described. The kinematics and dynamics of the mobile robot are presented. The design of control system is implemented for position and orientation angle in order to control the linear and angular speed of the omnidirectional robot. The designs of fuzzy controllers are performed and then these are used for the control of the holonomic 4-wheel-driven soccer robots. The designed fuzzy control algorithm has been extensively tested in simulation and provided satisfactory results in run time. The controller presented in this paper provides an optimal solution to minimize the differences between the reference trajectory and the current output. The obtained results demonstrate the effectiveness of proposed algorithms in robot soccer control.

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Keywords: Robot Soccer; fuzzy control; obstacle avoidance.

1. Introduction

Recently numerous significant developments have been proposed for mobile robot system control. Mobile robot dynamics are nonlinear and has many uncertain factors. These are caused by friction, vibrations, payload variation, slippage between wheels and terrain and disturbance. Therefore it is difficult to obtain exact mathematical model for the design of control system. Since the modelling of these parameters is difficult they limit the effectiveness of

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control systems. Based on nonlinearities and uncertainty factors various control systems have been designed. Watanabe et al. (1998) considered feedback control, Liu et al. (2008) considered nonlinear controller design through trajectory linearization, Rossomando and Soria (2015) considered adaptive neural PID control, Hashemi et al.(2011) considered fuzzy PI control of omnidirectional robots.

Number of research works has been published on the design of control system of omniwheel robots. Omniwheel robot is a type of mobile robot that moves in all directions and very suitable for applications in dynamic environments. Omnidirectional robots are used in robot soccer game of the RoboCup competition. There are a number of robot soccer teams that have annual RoboCup competitions in the different countries. NEUIslenders team is one of them that has been designed in Applied Artificial Research Centre of Near East University. Abiyev et al. (2014), Abiyev et al. (2013) and Abiyev et al. (2012) are described the control structure of robot soccers.

In robot soccer game the environment where soccer robots move is characterized with fast changing dynamic areas with moving dynamic obstacles. Control system of these soccer robots includes a set of algorithms. These are vision module, decision making, path finding, obstacle avoidance and motion control modules. The design principles of these modules are represented in the papers of Abiyev et al. (2015) and Abiyev et al. (2010). Motion control module of robot soccer is one of the basic modules that controls the dynamics of the robot and drives the robot to the destination point. The obtaining of high accuracy control system is becoming important problem in conditions of uncertainty factor such as unknown frictions and disturbances.

Different approaches have been used to design control systems. These are sliding-mode control used by Mu et al. (2015), neural-networks used by Li et al (2015), fuzzy approach used by Masmoudi et al. (2016), Pena et al. (2015) and Treesatayapun and Guzman-Carballido (2009), neuro-fuzzy approach used by Philip Chen et al. (2014), fuzzy wavelet network used by Abiyev and Kaynak (2008), and Tsai et al. (2014), type-2 fuzzy approach used by Abiyev and Kaynak (2010), Abiyev et al. (2013), Hsiao and Wang (2013) are presented. Watanbe et al. (1998), Hashemi et al. (2011) uses PID and fuzzy control system for omni-directional robot. Masmoudi et al. (2016) design fuzzy PI controllers for goal position and orientation angle. The authors also designed two fuzzy controllers to control robot linear velocities and robot angular velocities. Liu et al. (2008) use trajectory linearization control based on linearization among a nominal trajectory. Here a nonlinear dynamic system is transformed to a linear system via a nonlinear coordinate transformation and a nonlinear state feedback. Hsiao et al. (2013) uses type-2 fuzzy system for sliding mode control of robot. As shown in these researches fuzzy logic is used as one of better technique for designing controllers. In this paper, fuzzy system is used for the control of omnidirectional robot. The fuzzy rules are designed for the fuzzy controller and applied for mobile robot control.

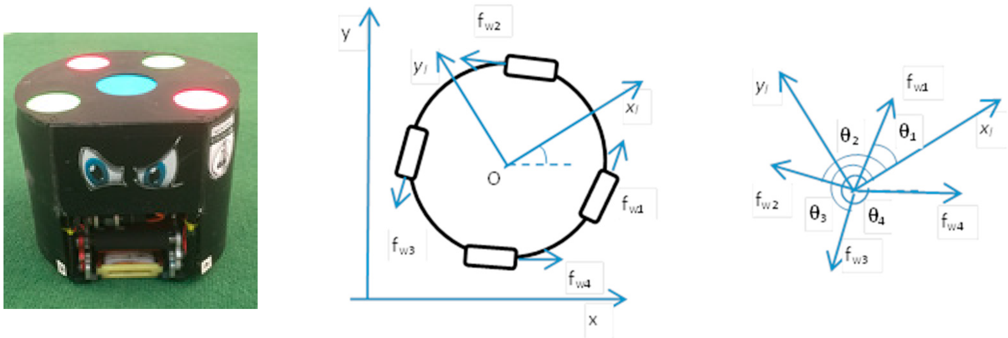
The paper is organized as follows. Section 2 describes the structure of control system of soccer robots. In section 3 the modeling of omnidirectional robot and the design of a fuzzy controller for soccer robot control are presented. In Section 4, the simulation studies and real life application are presented.

2. Kinematics and Dynamics of the Mobile Robot

The omnidirectional soccer robots and their control system are designed and manufactured in our research laboratory. The holonomic wheels with 3 degrees of freedom are used to design soccer robots. Abiyev et al. (2014), Abiyev et al. (2016) are presented the design modules of soccer robots. Fig.1(a) depicts the designed holonomic robot soccer. The soccer robot has four omni-wheels with a diameter of 61mm each. The wheel orientation of the robot is 30 degrees with the horizontal axis in front wheels, and 45 degrees with the horizontal axis in rear wheels (Fig.1(b)). The robot omni-wheels are connected to brushless DC motors and controlled by brushless DC motor drivers called Electronic Speed Controllers (ESC). Motor drivers are driven by a microcontroller. Microcontroller is connected to the computer via a wireless link.

The designed omnidirectional robot is used in NEUIslenders robot soccer team. Robot has decision making module that make the strategic planning of soccer robot to define its new position as it was mentioned by Abiyev et al. (2015). In the results of the decision making, the new coordinates of the soccer robots are computed. Using these coordinates soccer robots moves to its target locations. The control of position and rotation of the soccer robot is implemented by fuzzy controller which is presented in this paper. A fuzzy controller compute control signals for the wheels of the robot soccer

Omnidirectional robot has three degrees of freedom and they can move in any direction depending on velocity of each wheel. By combaining the movement of all whells the robot can move forward, backward, left and right directions. Using the relations between wheels and robot velocities the mathematical modeling of the kinematic will be performed. Fig. 1(a,b) describes robot position using local moving and global coordinates. Let's represent robot location and orientation in global and local (moving) coordinate system as $[x\ \ y\ \ \phi]$ and $[x_l\ \ y_l\ \ \phi_l]$ correspondingly. By transforming the global coordinates to the local movement the obtaining robot destination point is performed. The global coordinates of robot is represented by $Z=[x\ y\ \phi]^T$. Here x and y are global cordinates of robot center (point O), ϕ is anglular difference between global and local movement frames.



(a) (b) (c)

Fig.1. (a) Robot-soccer, (b) wheels positions of the robot-soccer, (c) forces

The transformation matrix is used to map the global coordinates of the robot $Z=[x\ \ y\ \ \phi]^T$ into the local coordinates $Z_l=[x_l\ \ y_l\ \ \phi]^T$. The moving coordinates can be determined as

$$Z_l=R*Z \quad or \quad \begin{bmatrix} x_l \\ y_l \\ \phi \end{bmatrix} = \begin{bmatrix} cos\phi & sin\phi & 0 \\ -sin\,\phi & cos\,\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ \phi \end{bmatrix} \tag{1}$$

Here R is transformation matrix between global coordinates and moving coordinates

Let's consider dynamics of four-whelled omniderictional robots using the driver torque, the traction forces, angular velocity and angular acceleration. The motor charcteristics has great affect on robot behaviour. During the design of controller we need consider the motor characteristics. If we denote traction forse values of each wheels by f_{wi}, i=1,…,4 then the forse matrix will be writen as

$$F_m=[f_{w1}\ f_{w2}\ f_{w3}\ f_{w4}]^T \tag{2}$$

The applied forces and moment will be denoted as

$$F_l=[F_{lx}\ F_{ly}\ M_z]^T \tag{3}$$

As we denoted above the robot location and orientation in global and local (moving) coordinate system are presented as $[x\ y\ \phi]$ and $[x_l\ \ y_l\ \ \phi_l]$ correspondingly. The same approch we can use for velocities in global and local coordinat system, that is $[\dot{x}\ \ \dot{y}\ \ \dot{\phi}]$ and $[\dot{x}_l\ \ \dot{y}_l\ \ \dot{\phi}_l]$. The four omniwheels are located at the angles of θ_i (i=1,2,3,4) relative to the local coordinate system. If we accept the moving axis as x_l as a starting point and count degrees in the counter clockwise direction then we will have θ_1=60º, θ_2=120º 0, θ_3=225º.

$$F_l = A\ \ F_w \quad \text{or} \quad \begin{cases} F_{lx} = f_{w1}\,cos(60) - f_{w2}\,cos(60) - f_{w3}\,cos(45) + f_{w4}\,cos(45) \\ F_{ly} = f_{w1}\,sin(60) + f_{w2}\,sin(60) - f_{w3}\,sin(45) - f_{w4}\,sin(45)\ ; \\ M_z = Lf_{w1} + Lf_{w2} + Lf_{w3} + Lf_{w4} \end{cases} \tag{4}$$

Here L is the distance from the centre of robot. f_{w1}, f_{w2}, f_{w3}, f_{w1} are traction forces applied on the wheels.

Raul and Forster (2006) and Baede (2006) have considered the some aspects of kinematic and dynamic modeling of omnidirectional robots. Let's determine the final velocities of wheels, the velocity of the mobile robot and also angular velocity of the robot. The individual velocities of the four wheels are denoted as [v_1, v_2, v_3, v_4]^T. The velocity vector is obtained by taking the derivative of the robot position. The robot velocity and tangential rotational speed of the robot will be represented by $\dot{Z}$ =[$\dot{x}$ $\dot{y}$ z]^T=$\left[v_x \; v_y \; \omega_z\right]^T$. The robot wheel can move in two directions: horizontal and vertical. The sum of these two directions will result the movement of the robot. Taking into account the mentioned, for all wheels we can obtain the following as given in Abiyev et al. (2014). The wheel geometry in terms of robot speed and angular velocity can be represented as.

$$\dot{Z}_w = Q * \dot{Z}_l \;\; or \qquad \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{bmatrix} = \begin{bmatrix} -\sin\theta_1 & \cos\theta_1 & 1 \\ -\sin\theta_2 & \cos\theta_2 & 1 \\ -\sin\theta_3 & \cos\theta_3 & 1 \\ -\sin\theta_4 & \cos\theta_4 & 1 \end{bmatrix} \times \left[v_x \;\; v_y \;\; w_\omega\right]^T \tag{5}$$

Here θ_i, i=1,…,4 angles of wheels.Q is transformation matrix. v_1, v_2, v_3, and v_4 are motor speeds. v_x *and* v_y are the speed of robot in horizontal and vertical direction, R_ω is the rotation speed.

3. Control Structure

The control system used for control of omnidirectional robot is given in Fig.2. In this structure the difference e(k) between the plant's output signal y(k) and the set-point signal g(k) is determined. Using the error e(k) the change in error e'(k) and the sum of error ∑e(k) are determined. In the figure, D indicates differentiation operation and ∑ indicates integration operation. Using these input signals the fuzzy system is used for closed-loop control system.

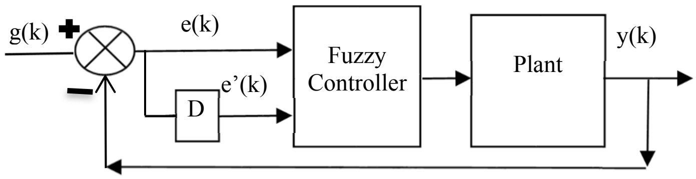


Fig. 2. Structure of Z number based fuzzy control system.

Let's determine the speed that will lead the robot from start position [x y ϕ] to the end reference position [x_r y_r ϕ_r]. The output control signal of fuzzy controller will be function of error and change in error signal. Using the diference between reference positions and real current positions the values of errors are determined. This operation can be expressed using the following formulas.

$$E= Current - Ref \tag{6}$$

Here Ref is reference signals determined for position and velocity of the mobile robot in global coordinates, Ref=[x_d y_d v_d]^T. The difference between reference and real position will be calculated as

$$\begin{bmatrix} e_x \\ e_y \\ e_\theta \end{bmatrix} = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix} - \begin{bmatrix} x_d \\ y_d \\ \theta_d \end{bmatrix} \tag{7}$$

To control the position of mobile robot the velocities of the robot wheels that will lead the robot from start position to the referrence position should be determined. Using error signal we can determine the derivatives of error signals. Error and change in error signals are used to determine the output of the fuzzy controller.

$$\begin{bmatrix} u_x \\ u_y \\ u_\theta \end{bmatrix} = f(\begin{bmatrix} e_x & \dot{e}_x \\ e_y & \dot{e}_y \\ e_\theta & \dot{e}_\theta \end{bmatrix}) \tag{8}$$

The control of mobile robot is performed using two input signals- error and change in error. A tabular representation of the rules for the position control is given in Table 1. Table describes the knowledge about how to control the robot using given the error and its derivative as inputs. This rule base is a kernel of the fuzzy controller that is used for controling the positions and rotation angle of the mobile robot. The accuracy of a fuzzy control system depends on input variables as well as the expert rules and the membership functions; therefore it is important for them to be chosen carefully. In knowledge base, the IF-Then rules demonstrate the association between input parameters and output control signal. On the base analysis of the dynamic plants, the KB describing input-output association is designed. Using error and change of error the coresponding value of control signal is determined. This signal can control the linear and angular speeds of the mobile robot. When the robot is far from the goal position then it will have large value of velocity. When robot will be near goal, according rule base controller will generate small control signal that will correspond to the small value of velocity. By using error value the velocity of the robot will be regulated.

The inputs are the error and change in error of [x y θ] signals. The values of input and output signals – error, cahange in error and control signals are represented by linguistic values. The simulations have been done and the position traking error and angle tracking error are presented in Fig. 3(a,b). The values of error and change in error are scaled in interval [-1 1]. The triangular membership function is used to represent the lingustic values.

Table 1. The rule base of controller

		Change in Error ($e^{\cdot}$)						
		NL	NM	NS	Z	PS	PM	PL
Error (e)	NL	PL	PL	PL	PL	PM	PS	Z
	NM	PL	PL	PL	PM	PS	Z	NS
	NS	PL	PL	PM	PS	Z	NS	NM
	Z	PL	PM	PS	Z	NS	NM	NL
	PS	PM	PS	Z	NS	NM	NL	NL
	PM	PS	Z	NS	NM	NL	NL	NL
	PB	Z	NS	NM	NL	NL	NL	NL

Fuzzy composıtıon is presented for designing of an inference engine of fuzzy rule-based system. The mathematical background of the fuzzy inference system based on interpolative mechanism is presented in next section.

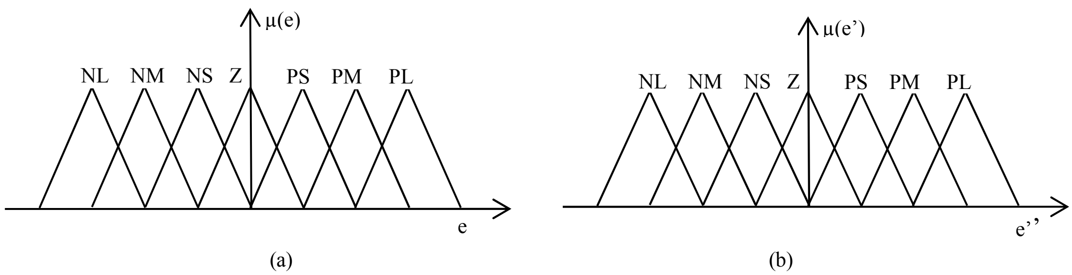


Fig.3. The values of error (a), cahange in error (b).

Using the table fuzzy If-Then rule base is developed. Since there are seven membership functions for $e(k)$ and $e'(k)$ respectively, there will be 49 fuzzy rules.

Using the rule base the output of the value of control signal is determined. The determination of the output is performed using a fuzzy inference engine. The inference engine is implemented using max-min composition. The current values of input coming signals are entered to the rule base, after fuzzification the membership degree of each input signal to current fuzzy term in RB is calculated.

Inference of fuzzy system is performed by the following formula

$$\tilde{X}1, \tilde{X}2 \rightarrow \tilde{Y} \tag{9}$$

where $X\tilde{1}, X\tilde{2}$ are fuzzy values of error, cahange in error, respectively, $\tilde{Y}$ is a control signal sent to the motors of a robot. After defining the membership degrees of the input signals for each active rules in rule base the fuzzy logic inference is performed using max-min composition of Zade.

$$\mu(y) = \max_{x1,x2} \min\{\mu_{X1}(x1), \mu_{X2}(x2), \mu_R(x1, x2, y)\} \tag{10}$$

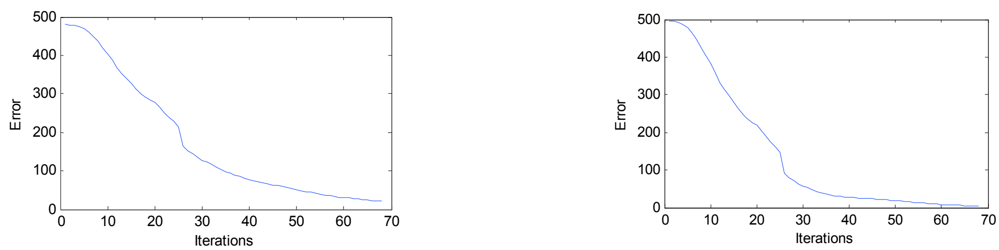
Using the "Centre of average" method the defuzzification process of fuzzy output signal is performed

$$y = \frac{\sum_{i=1}^{n} \mu(y_i) * y_i}{\sum_{i=1}^{n} \mu(y_i)} \tag{11}$$

The formulas (9) and (11) are used to determine output of fuzzy logic system.

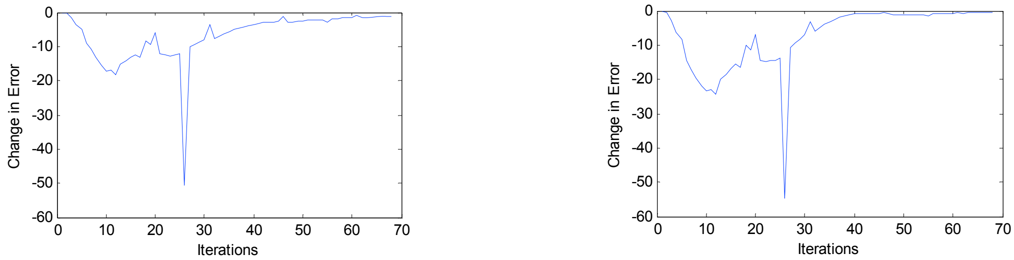
4. Experimental studies

At first, the designed fuzzy control algorithms are tested using a simulation software package named grSim, then they are implemented on real omnidirectional soccer robots which are designed in our research laboratory. The designed robots are used in RoboCup competition. Fuzzy controller design is based on the approaches that is given in sections 3 and 4. The control of positions and orientation angle of mobile robot is implemented by controlling linear and angular velocities of mobile robot, The simulations have been done when omnidirectional robot moves from start position to target position. During designing of control circuit the problem was reaching target position and decreasing error on the output of the controlled object. The simulation results obtained for position control are given in Fig.4. and Fig.5. Fig. 4 depicts the plots of errors in x (Fig.4(a)) and y (Fig.4(b)) directions. As shown after some iteration the position errors in x and y directions become zero. Because of the targeted position is the ball and omnidirectional robot is approaching to the ball (as a target), for getting the ball we subtract half of diameters of the ball from the x target directions. That is target position for the robot will be (x_d-d_{ball}/2, y_d). Here x_d and y_d are desired x and y positions, d_{ball} is ball's diameter. For this purpose in Fig.6(a) the error e_x does not become exactly zero. The small value shown in Fig.4(a) is related to the d_{ball} ball's diameter.



(a) (b)

Fig. 4. Error plot in: (a) x, and (b) y directions

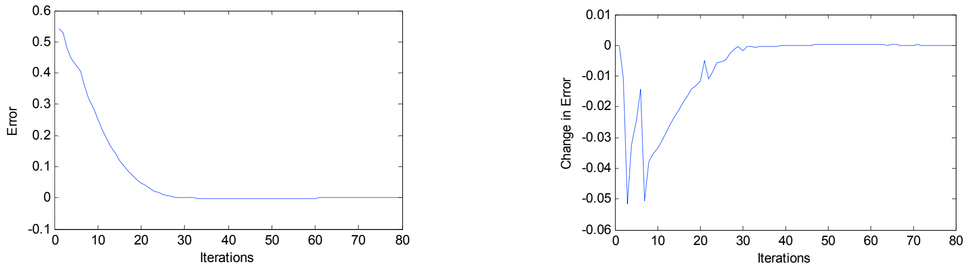


(a) (b)

Fig. 5. Plot of change in error in: (a) x, and (b) y directions

Fig. 5 depicts the value of change in errors of x (Fig.5(a)) and y (Fig.5(b)) directions. As shown when errors in x and y directions are approaching to zero (Fig4), the change in errors are also approaching to zero (Fig.5).

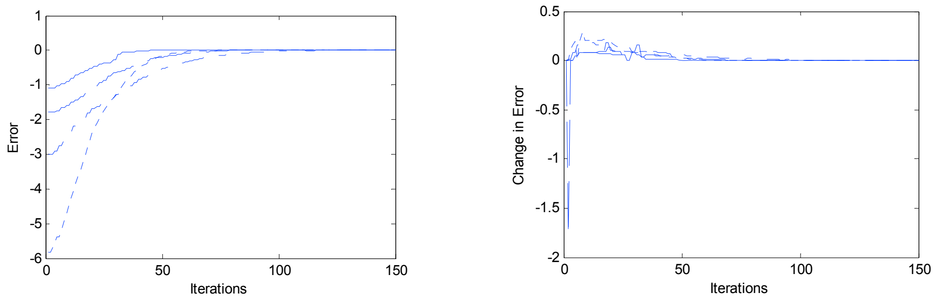
In next stage the test of the control of the rotational angle of the robot has been performed. The simulation has been performed using different target angle values. Fig. 6 depicts the plot of the error's values (Fig.6(a)) and change in error's values (Fig.6(b)) of rotational angle.



(a) (b)

Fig.6. Plot of error and change in error of angle. Rotational angle is 30^o.

The robot can navigate in four quadrants with different positions. The simulation has been done using different orientation angles, such as -45^o, -90^o, -180^o and -330^o degrees (Fig.7). Fig.7(a) depicts error, Fig.7(b) – chage in error signals. Here solid line is the plot of the values of errors for the orientation angle 45^o, dashed line - 90^o, dash-dotted line- 180^o and dotted line -330^o



(a) (b)

Fig. 7. Plot of errors (a) and change in errors (b) for orientation angles of 45^o (solid line), 90^o (dashed line), 180^o (dash-dotted line) and 330^o (dotted line)

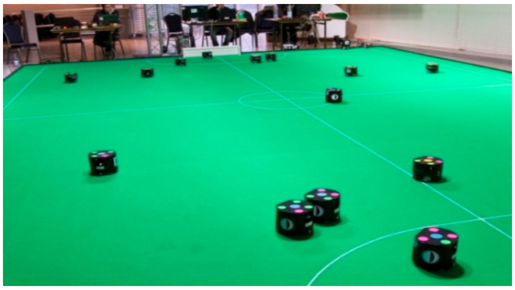


Fig. 8. The real game in RoboCup competition: NEUIslenders soccer robot team playing football game

The designed control algorithms are implemented on omnidirectional soccer robots of NEUIslenders team. Fig. 8 depicts the soccer robots of NEUIslenders team that use the fuzzy controller in a football game of RoboCup competition. The obtained experimental results satisfies the application of fuzzy controllers in control of omnidirectional robots. Detailed description of the robot navigation is given in web-pages http://staff.neu.edu.tr/~rahib/aairc/research_groups.htm or http://robotics.neu.edu.tr/

5. Conclusions

The design of fuzzy controller for control of omnidirectional robot is proposed in this paper. The kinematics and dynamics of the mobile robot is described. The designed algorithm of fuzzy controller is presented. The proposed algorithms are used for the design of controller for control of positions and rotational angle of mobile robot. The designed control algorithms presents efficient navigation of soccer robots which are designed and manufactured in our research laboratory. The proposed controllers have been tested in simulation and provided satisfactory results. The performance characteristics of designed control systems have been constructed. In the result of the application of fuzzy controller the required regulation time for reaching the new position and also orientation angle is decreased. In a future research the problem introduced in this paper will be considered using Z number based fuzzy approach. The use of Z number system will allow to increase the performance of the control system.

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