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Fuzzy Fine tuning of an Optimized PID Control Scheme for Mobile Robot Trajectory Tracking

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ABSTRACT
This paper present an efficient robust design method of PID control scheme based on using fuzzy logic and particles swarm optimization (PSO) method for trajectory tracking of mobile robot. Two PID controllers are used. Parameters of PID controllers are optimized offline using PSO and fuzzy controller is used for tuning the parameters online . The two optimized PID controllers are used for speed control and azimuth control. The online fuzzy tuning in the designed control scheme work well when there are variations in the plant parameters and changes in operating conditions.

Keywords
Mobile Robot, Particles Swarm Optimization,fuzzy control, PID Controller, Trajectory tracking.

1. INTRODUCTION
Mobile robots have been used in many applications such as moving material in idustries . They can be found in wide areas such as industry, ports and agriculture, because they have a good loading capability[1]. A mobile robot is a wheeled vehicle capable of moving autonomously. Cleaning robots and cargo delivery can work automatically and are performing various routine tasks [2,3,4]. In cargo transport task, the robots move to the target location following their path. It is essential for these robots to precisely track the path from the starting location to the target location, carrying as much cargo as possible . Therefore, motion control is one of the most fundamental topics for mobile robots. Many types of controllers are used for controlling the mobile robot [5,6,7].

PID controllers have been used to control about 90% of industrial processes [3]. The main problem of this simple controller is the correct selection of the PID gains and the fact that by using fixed gains, the controller may not give the required control performance, when there are variations in the plant parameters and operating conditions. An online tuning process must be performed to insure that the controller can deal with the variations of parameters and environment [4]. To tune the gains of PID controller, there are numbers of strategies, the most known, which is frequently used in industrial applications, is the Ziegler-Nichols method , genetic algorithm GA, etc. Also , PSO was another method for tuning procedure[5]. PSO has been motivated by the behavior of organisms, such as fish schooling and bird flocking. Generally, PSO is characterized as a simple concept, easy to implement, and computationally efficient. [7]. In this paper, PSO is used as an optimization tool for the parameters of PID controllers offline and fuzzy system is used for an online fine tuning of these parameters. This paper has been organized as follows: in section 2 mathematical model of mobile robot is described. In section 3, the particle swarm optimization method is reviewed. Section 4, describes how PSO is used for the optimization of the parameters of the PID conrollers for mobile robot .Section 5 describe the method of using fuzzy controller for tuning the parameters online. Simulation results are presented in section 6.

2. MATHEMATICAL MODEL OF MOBILE ROBOT
The mobile robot is shown in Figure 1. A robot must have a minimum of three wheels in order to work. Most mobile robots require two motorized wheels and at least one wheel for balance [8]. The system moves by driving the two independent wheels.

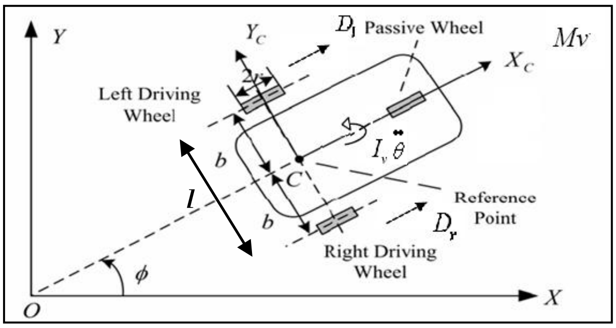


Figure 1: Model of mobile robot mmmmobile mobile robot

Let us consider the kinematic model (motion without considering the forces that affect the motion , it use the geometric relationships) for an autonomous vehicle. The rotation angle of the wheel about its horizontal axle is denoted by φ(t) . Let $\varphi_r(t)$ be the rotation angle of the right wheel and $\varphi_l(t)$ be the rotation angle of the left wheel. The configuration of the mobile robot can be described as:[9]:

$$q = (x_{c,} y_c, \theta, \varphi_r, \varphi_l) \qquad (1)$$

where: x_c *and* y_c are the two coordinates of the origin C of the moving frame, θ is the orientation angle of the mobile robot (of the moving frame). The vehicle velocity *v* can be found as [3]:

$$\mathrm{v} = \frac{\mathrm{R(w_r+w_l)}}{2} \qquad (2)$$

w_r is the angular velocity of the right wheel and w_l is the angular velocity of the left wheel.

The position and the orientation of the mobile robot are given as: [7, 3]:

$$\dot{x} = \mathrm{v}\cos(\theta) = (R\ (w_r + w_l)\cos(\theta))/2 \qquad (3)$$

$$\dot{y} = (R\ (w_r + w_l)\sin(\theta))/2 \qquad (4)$$

$$\dot{\theta} = R(w_r + w_l)/2b \qquad (5)$$

Finally, the kinematics model can be represented by :

$$\begin{bmatrix} v \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} R/2 & R/2 \\ R/2b & -R/2b \end{bmatrix} \begin{bmatrix} w_r \\ w_l \end{bmatrix} \quad (6)$$

The kinematic model has been used for motion control and this model is valid if the robot has low speed, low acceleration and light load [9]. Dynamic models consider the forces acting on the vehicle. Dynamic equation of wheeled mobile robot is described as in [10]:

$$Ms\,\dot{v} = F_r + F_l \quad (7)$$

$$I_w\,\ddot{\theta}_i + c\,\dot{\theta}_i = ku_i - rF_i \qquad i = r, or\ l \quad (8)$$

Where ,

Ms : mass of robot , φ : azimuth of robot .

v : velocity of robot, I_w : moment of inertia of wheel.

c : viscous friction factor , k : driving gain factor.

r : radius of wheel, θ_i : rotational angle of wheel.

u_i : driving input, F_r ,F_l: right and left driving force.

I_v : moment of inertia .

l : distance between left and right wheel .

The geometrical relationships among variables φ, v , θ_i are given by:

$$r\dot{\theta}_r = v + l\dot{\varphi} \quad (9)$$

$$r\dot{\theta}_l = v - l\dot{\varphi} \quad ... (10)$$

The state model with manipulated variable as u=[u_r u_l] and the output variable as y=[v , θ] Yield the following equation:

$$\dot{x} = Ax + Bu \quad (11)$$

$$y = Cx \quad (12)$$

Where:

$$A = \begin{bmatrix} a_1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & a_2 \end{bmatrix}, \quad B = \begin{bmatrix} b_1 & b_1 \\ 0 & 0 \\ b_2 & -b_2 \end{bmatrix}, \quad C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

with,

$$a_1 = \frac{-2c}{(Ms * r^2 + 2I_w)}, \quad a_2 = \frac{-2cl^2}{(I_v r^2 + 2I_w l^2)}$$

$$b_1 = \frac{kr}{(Ms * r^2 + 2I_w)}, \quad b_2 = \frac{krl}{(I_v r^2 + 2I_w l^2)}$$

The relation between the controller output torques u_r and u_l with variables u_v and u_φ are given in equations (13) and (14.) below:

$$u_r = u_v + u_\varphi \quad (13)$$

$$u_l = u_v - u_\varphi \quad (14)$$

and error equations are:

$$e_v = v_d - v \quad (15)$$

$$e_\varphi = \varphi_d - \varphi \quad (16)$$

where v_d , φ_d are the desired velocity and the desired azimuth, respectively. v , φ are the actual velocity and the actual azimuth of the robot, respectively.

3. PARTICLE SWAM OPTIMIZATION

Particle Swarm Optimization (PSO) is a procedure used to explore the search space of a given problem to find the values required to maximize a particular fitness function. [11]. [12]. This technique comes from the idea of swarm like fish schooling and bird flocking. It is noticed that birds find food by flocking. In the PSO algorithm a flock of particles are represented in the search space with randomly chosen velocities and positions. The velocity of each particle, is updated according to flying experience and the other particles flying experience. For example, the i^{th} particle is represented as $x_i = (x_{i,1}, x_{i,2}, \dots, x_{i,d})$ in the d-dimensional space. The best previous position of the *i th* particle is recorded and represented as:

$$Pbest_i = (Pbest_{i,1}, Pbest_{i,2}, \dots, Pbest_{i,d})$$

The index of best particle among all of the particles in the group is $gbest_d$. The velocity for particle i is represented as $v_i = (v_{i,1}, v_{i,2}, \dots, v_{i,d})$ The modified velocity and position of each particle can be calculated as shown in the following equations[13]:

$$v_{i,m}^{t+1} = w.v_{i,m}^{t} + c_1 * Rand(\,) * \left(pbest_{i,m} - x_{i,m}^{(t)}\right) + c_2 * rand(\,) * (gbest_m -) \quad (17)$$

$$x_{i,m}^{(t+1)} = x_{i,m}^{(t)} + v_{i,m}^{(t+1)} \quad (18)$$

$$i = 1,2,\dots,n \;\; ; \quad m = 1,2,\dots,d$$

where,

n : Number of particles in the group.

d : Dimension, t : Iteration.

$v_{i,m}^{(t)}$: Velocity of particle i at iteration t . w : Inertia weight factor, c_1, c_2: Acceleration constant.

$x_{i,d}^{(t)}$: Current position of particle

$Pbest_i$: Best previous position of the ith particle.

$gbest$: Best particle among all the particles.

4. PSO OPTIMIZED PID CONTROLLER

In this paper the PSO algorithm is used offline to find the optimal parameters for two PID controllers used for the control of velocity and azimuth of mobile robot

Each particle contains six members P_1, I_1 and D_1 (parameters of velocity controller), and P_2 , I_2 and D_2 (parameters of azimuth controller). The search space has six dimensions and particles must 'fly' in six dimensional space. In this work The mean square error is used as a fitness function.

Mean Square Error (MSE) is given as:

$$MSE_{total} = \left(\frac{1}{n}\sum_{k=1}^{n}\left(e_\theta(k)\right)^2\right) + \left(\frac{1}{n}\sum_{k=1}^{n}\left(e_v(k)\right)^2\right) \quad (19)$$

5. FUZZY CONTROLLER

Fuzzy logic controllers have been used in many applications . In the control systems, fuzzy logic is considered in the control of linear, nonlinear and complex nonlinear plants such as robotics power plants and induction motors[14,15,16,17]. Basics of a fuzzy model are explained in [18]:

5.1 Fuzzy tuning Control Scheme (FSC-PID)

In this section a Fuzzy tuning Control (FSC-PID) scheme that uses two fuzzy controllers is used to tune the parameters of the two PID controllers. Each fuzzy controller has two inputs and three outputs used to tune the three parameters (Kp, Ki and Kd),of the PID controller as shown in Figure 2 . This kind of controller is an online controller. Many papers explain the FSC-PID method [18, 19,20] . The fuzzy controller is the master controller which has the ability to tune the PID parameters and PID controller is the slave controller. Figure 2 represents FSC-PID scheme. Each Fuzzy controlle in this scheme has two inputs (the error and change of error) and three outputs. (s_p, s_i, and s_d) which represent the values that used to change PID gains (K_p, K_i and K_d). The new values of the two PID parameters are found from the following equation[19,20]

$$K_h = K_{h_{min}} + (K_{h_{max}} - K_{h_{min}})\ s_h \qquad (20)$$

S_h is the output of the fuzzy controller with subscript h represents *p, i,* and *d* for each controller.

The maximum and minimum values appear in eq.(20) are determined offline using PSO algorithm. Membership functions are chosen as shown in figure 3. Mamdani method is used in fuzzy inference system. Defuzzification method is center of area.

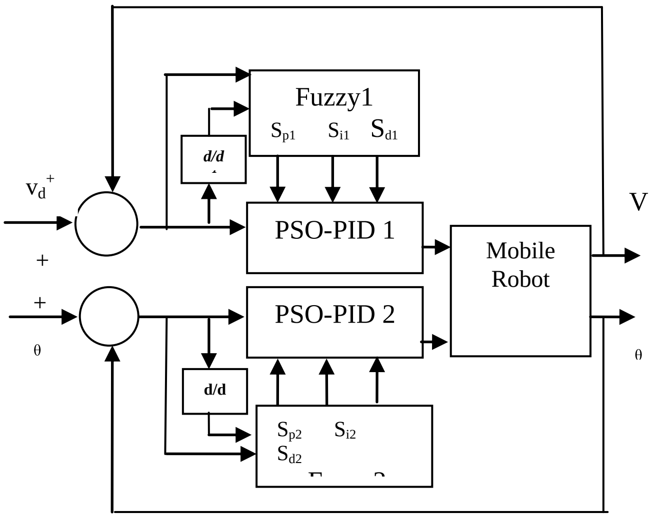
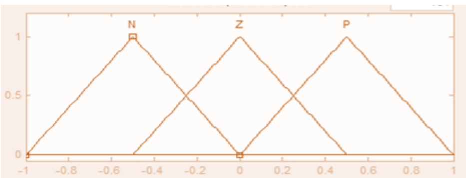
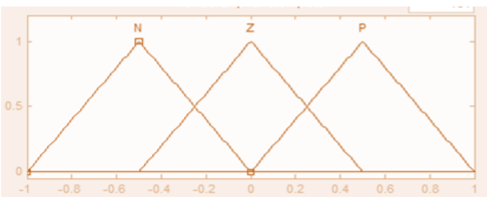


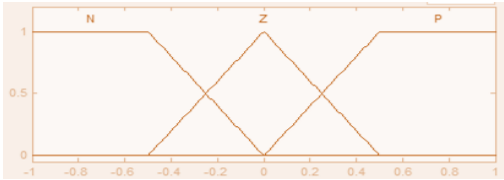
Figure2 : The proposed control scheme



a) Input 1



b) Input 2



c) Output

Figure 3 Membership functions

Fuzzy rules used in FLC are shown in table 1.

Table 1: Fuzzy rules

S_h	e(t)			
ce(t)		P	Z	N
	P	P	P	Z
	Z	P	Z	N
	N	Z	N	N

6. SIMULATION RESULTS

Consider a mobile robot, the values of physical parameters shown in Table 2 are used [21].

Table 2: The physical parameters of mobile robot

Parameter	Value	Unit
I_v	10	$kg.m^2$
Ms	200	Kg
L	0.3	M
I_w	0.005	$kg.m^2$
C	0.05	kg/s
R	0.1	M
K	5	

The following PSO parameters are used to obtain the optimal performance of the controller :

Wmax=0.88 , Wmin=0.5; $c_1 = c_2 = 1.2$;

By doing several experiment using different values .The following values for population size and number of iterations are considered to be acceptable.

Population size=30; Number of iteration =40. The result obtained in 40 iterations as [214, 533, 257] and [358, 404, 176] for the two PID controllers respectively. These values are considered as parameters of the two optimal PID controllers that give the lowest MSE.

The system is tested for two different cases as follows :
1) Circular trajectory given by a reference velocity v_d of 1 [meter/sec] and a reference azimuth θ_d given as :

$$\theta_d = \frac{(2*\pi)t}{5} \ [rad]$$

with, $0 \le t \le 5$.

Figure 4 shows the velocity error, Figure 5 shows the azimuth error, Figure 6 shows the actual and desired path for circular trajectory

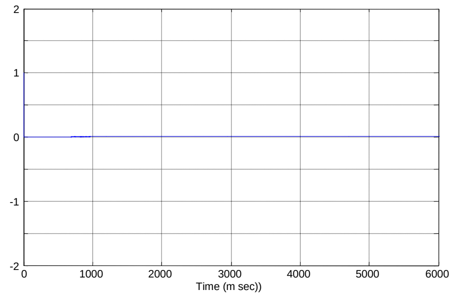


Figure 4: The error in velocity (circular)

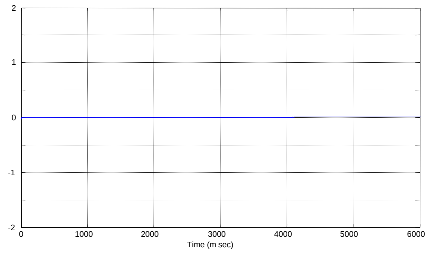


Figure 5: The error in azimuth (circular)

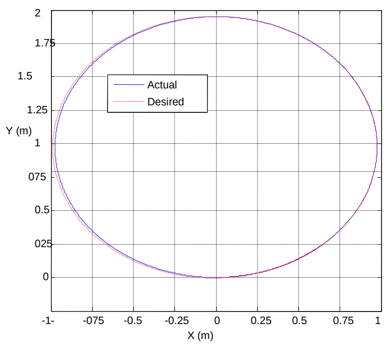


Figure 6: circular trajectory tracking

2) A square trajectory.

Figure 7 shows the error in azimuth and Figure8 shows the error in velocity . Figure 9 shows the desired and actual square trajectory.

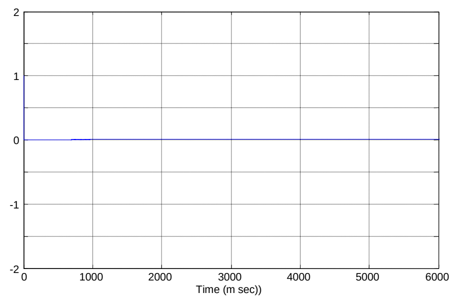


Figure 7: The error in velocity(square)

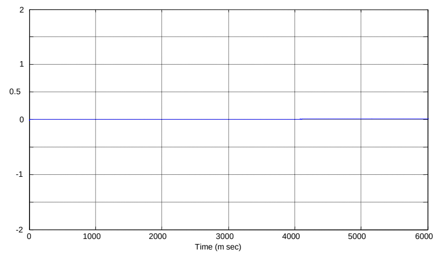


Figure 8: The error in azimuth (square)

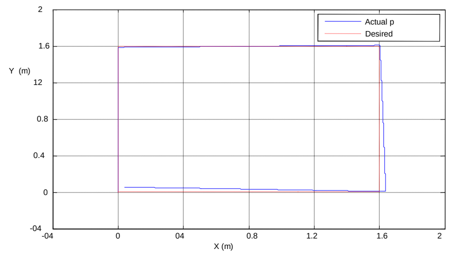


Figure 9: square trajectory tracking

7. CONCLUSION

Fuzzy tuned PSO optimized PID control scheme is proposed for trajectory tracking problem for mobile robot . The particle swarm optimization method is used offline for the optimization of the parameters of PID controllers and fuzzy system is used for online fine tuning of these parameters. The online tuning property of the proposed control scheme solve the problems of disturbance , different load conditions and system parameters variations . Results show good tracking performance .

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