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SPEED CONTROL OF A SHIP USING T-S FUZZY LINEARIZATION AND PREDATOR-PREY PIGEON INSPIRED OPTIMIZATION

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Abstract. *In this paper, an efficient speed control scheme is presented for a ship. At high surge speed of a ship, its mathematical model becomes nonlinear. For a nonlinear system, the traditional PID controller does not provide good quality results with the same parameters. To deal with this situation, the nonlinear model is first linearized using Takagi-Sugeno (T-S) fuzzy linearization. Then, for every rule, the control parameters of the PID controller are tuned and optimized based on a swarm intelligence optimizer called Predator-Prey Pigeon Inspired Optimization. Finally, the control scheme is defuzzified to get the global control. This method is simulated on the mathematical model of a ship called Cybership II and the results show that the proposed method is effective.*
Keywords: T-S fuzzy, Linearization, Ship, Speed control, Pigeon Inspired Optimization

1. **Introduction.** With the advancement of science and technology, the need of autonomous surface [1] and subsurface vessels is increasing. Therefore, the demand of efficient automatic control subsystems of an autopilot system is increasing. These autopilot systems should be efficient, robust and safe and they should be designed accordingly.

The control system design of under-actuated marine vessels can be categorized into two groups. One is steering control system and the other is speed control system [2]. A speed control system can reduce unnecessary change of speed, increase efficiency of engine, manage fuel consumption and reduce helmsman's exertion. Traditionally, a PID controller has been widely used in a cruise control system [3]. Since the speed of the vessel increases, the nonlinearity of its mathematical model also increases. As it crosses the linear region, a PID controller becomes less effective and/or efficient with the same parameters [4]. Thus, there is a need to design an efficient nonlinear control system.

T-S fuzzy logic system can be used as a universal approximator for linearization of nonlinear systems [5]. By using T-S fuzzy linearization, a nonlinear system is converted into some local linear systems at their respective linearization points, so that linear control theory can be applicable [6]. However, the linear control should be effective and efficient.

Any control system should be optimized for maximum efficiency, minimum rise, settling time and minimum overshoot. Primitively, optimization was done through experimentation but now many optimization algorithms can be used. These algorithms can be divided into two categories: single point based algorithm and population based swarm intelligence algorithm. A common example of the former is hill climbing algorithm. Population based swarm intelligence algorithms include Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), Artificial Bee Colony Optimization (ABC), Brain Strom Algorithm (BSA), Predator-Prey Optimization (PPO) [7], Pigeon Inspired Optimization (PIO) [8], etc.

Research has found out that homing pigeons have a special system by which they can sense the magnetic field of the earth. Sun is also supposed to be involved for its direction finding behavior. Moreover, they can follow different landmarks such as rivers, railways and roads in order reach to their destination. They may follow other pigeons that are familiar with the route [8]. In [9], pigeons are considered to use different navigational tools during different parts of their routes. Based on this behavior, a bio-inspired swarm intelligence optimization algorithm called Pigeon Inspired Optimization has been designed accordingly.

PIO can solve a lot of optimization problems with a quick convergence but it can trap into a local solution. To tackle this problem, PPO is integrated with PIO to have a better search ability with resistance to local optimal solution trapping. This algorithm called Predator-Prey Pigeon Inspired Optimization (PPPIO) can be used to tune and optimize PID control parameters for better efficiency [10]. In this paper, an efficient and effective design of speed control for marine vessels based upon PPPIO is presented.

2. **Mathematical Model of a Ship.** When a ship sails in the ocean, it has six degrees of freedom, which can be denoted by six differential equations [11]. The motion in six degrees of freedom can be denoted according to SNAME[1] (1950) notation as shown in Table 1 [12].

Table 1. Notation used for vessels [12]

DOF	Motion/Rotation	Force/Moments (Units)	Linear/Angular Velocity (Units)	Displacement/Angle (Units)
1	In x-direction (surge)	X (N)	u (m/s)	x (m)
2	In y-direction (sway)	Y (N)	v (m/s)	y (m)
3	In z-direction (heave)	Z (N)	w (m/s)	z (m)
4	About x-axis (roll)	K (Nm)	p (rad/s)	ϕ (rad)
5	About y-axis (pitch)	M (Nm)	q (rad/s)	θ (rad)
6	About z-axis (yaw)	N (Nm)	r (rad/s)	ψ (rad)

Assumption 2.1. [11] *The motion in heave, roll and pitch are very small ($\phi \approx \theta \approx z \approx 0$) as compared to the motion in other directions.*

According to Assumption 2.1, the motion of the ship is only considered in the horizontal direction with three degrees of freedom, i.e., surge u, sway v and yaw rate r. The equation of motion can be written in vectorial representation as follows:

$$M\dot{v} + C(v)v + D(v)v = \tau \tag{1}$$

where M is the mass and inertia matrix, $C(v)$ is the Coriolis and centripetal matrix and $D(v)$ is the damping matrix. τ and $v = [u, v, r]^T$ are the applied force (and moment) vector and (linear and angular) velocity vector respectively.

Assumption 2.2. *It is assumed that the ship has homogeneous mass distribution and xz-plane symmetry (i.e., starboard-port symmetry).*

Therefore, it is implied that the surge can be decoupled from sway and yaw rate in Equation (1). It means that any force applied in the surge direction may not affect the sway and yaw rate [13]. After decoupling, the surge equation can be written in component form as [11,14]

$$(m - X_{\dot{u}})\dot{u} - X_u u - X_{|u|u}|u|u - X_{uuu}u^3 = \tau_u \tag{2}$$

where τ_u is the sum of all forces in the surge direction and $X_{\dot{u}}$, X_u, $X_{|u|u}$ and X_{uuu} are the mass related parameters of the system. This equation includes both the linear and quadratic damping in order to cover low and high speed applications [11]. In [14], different experiments were conducted to calculate the coefficients of Equation (2). Cybership-II

[1]Society of Naval Architects and Marine Engineers

TABLE 2. Mass related parameters for Cybership II [14]

1	m	23.8
2	$X_{\dot{u}}$	−2.0
3	X_u	−0.7225
4	$X_{\|u\|u}$	−1.32742
5	X_{uuu}	−5.86643

(CS2) is a 1:70 down-scaled replica of a supply vessel having mass 23.8 kg and length 1.255 m. Some of the required values of Cybership II are given in Table 2 [14]. In this paper, only forward (or positive) speed is considered. Thus, we have $X_{|u|u} = X_{uu}$.

3. Controller Design via T-S Fuzzy Linearization. In order to design the speed control, the following sequence should be followed which is also shown in Figure 1.

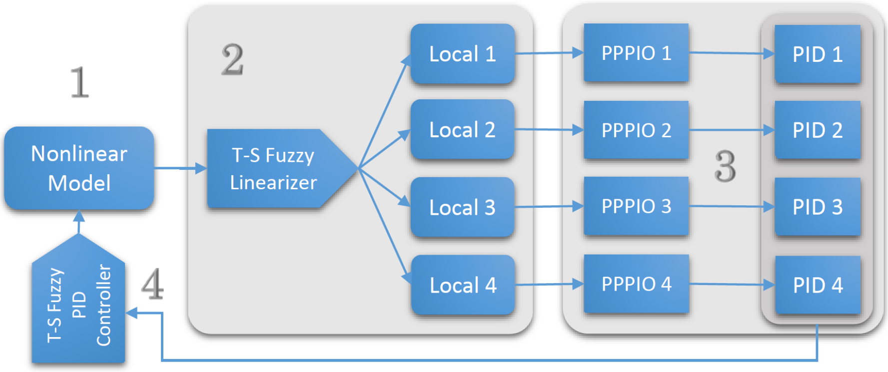

FIGURE 1. Process flow diagram of the proposed controller

3.1. State-space form. First, Equation (2) can be written in canonical state-space form as

$$f(x, \tau_u) = \dot{x} = ax + bx^2 + cx^3 + d\tau_u \tag{3}$$

where

$$x = u,\ a = \frac{X_u}{m - X_{\dot{u}}},\ b = \frac{X_{uu}}{m - X_{\dot{u}}},\ c = \frac{X_{uuu}}{m - X_{\dot{u}}} \text{ and } d = \frac{1}{m - X_{\dot{u}}}$$

3.2. Linearization. The Taylor series expansion of $f(x, \tau_u)$ can be written as

$$\begin{aligned} f(x, \tau_u) = {} & f(x_0, \tau_{u0}) + \left(\frac{\partial f}{\partial x}(x - x_0) + \frac{\partial f}{\partial u}(\tau_u - \tau_{u0})\right) \\ & + \frac{1}{2!}\left(\frac{\partial^2 f}{\partial x^2}(x - x_0)^2 + 2\frac{\partial^2 f}{\partial x \partial \tau_u}(x - x_0)(\tau_u - \tau_{u0}) + \frac{\partial^2 f}{\partial {\tau_u}^2}(\tau_u - \tau_{u0})^2\right) \\ & + \cdots \end{aligned} \tag{4}$$

and after ignoring higher order terms, for every rule i, we get

$$f_i(x, \tau_u) = \dot{x} \cong a_i x + b_i \tau_u + \alpha_i \tag{5}$$

where

$$a_i = \left.\frac{\partial f}{\partial x}\right|_{x_0, \tau_{u0}} \quad \& \quad b_i = \left.\frac{\partial f}{\partial \tau_u}\right|_{x_0, \tau_{u0}} \tag{6}$$

and

$$\alpha_i = f(x_0, \tau_{u0}) - a_i x_0 - b_i \tau_{u0} \tag{7}$$

The model in (3) can be linearized at m number of linearization points and their corresponding membership functions w_i, $i = 1, 2, \ldots, m$. If the number of approximation points is increased, then the accuracy of the linearized fuzzy model also increases as well as the computational cost, which is undesirable [15]. By Equations (3) and (7), it can be found as

$$\alpha_i = -bx_0^2 - 2cx_0^3 \tag{8}$$

In this study, there is a rule for every linearization point, and thus the number of rules is equal to the number of linearization points. The value of membership function must be maximum at its corresponding linearization point [16]. It should be noted that the constant term α_i may dominate the system behavior as compared to the other terms. Therefore, it cannot be neglected [17]. The membership function of every local system is given in Figure 2. The linearized equivalent global state-space model can be written as

$$\dot{x} = \frac{\sum_{i=1}^{m} w_i(x)(a_i x + b_i u + \alpha_i)}{\sum_{i=1}^{m} w_i(x)}$$

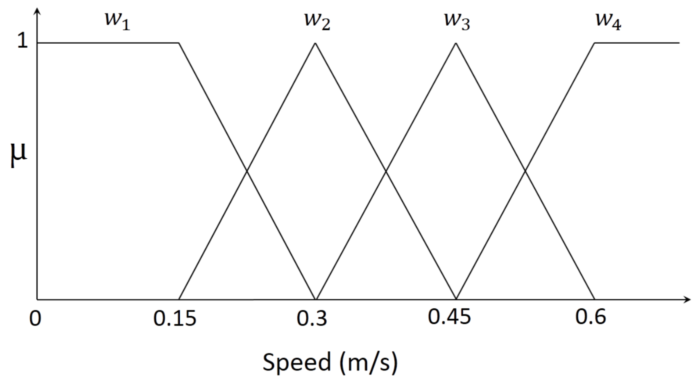

Figure 2. Membership functions corresponding to speed

3.3. **Local controllers design based on PPPIO.** A PID controller is constructed for each local model and it is optimized by PPPIO for maximum efficiency and best quality of control. In order to understand PPPIO, it is necessary to skim through PIO and PPO, as briefly explained next.

3.3.1. *Pigeon Inspired Optimization.* There are two types of tools used by homing pigeons which can be used in PIO. In the start of their journey, the pigeons rely on magnetic field of the earth and altitude of the sun [8]. This tool can be called Map and Compass Tool (MCT). During the last phase of their journey they rely less on MCT and rely more on recognition of landmarks named Landmark Recognition Tool (LRT).

First each pigeon i is placed in the search space with random position X_i and velocity V_i. Using MCT at every instant, the position of the pigeon is calculated and the best position is found. Using LRT, in every generation, half the number of pigeons is decreased by N_p. After specified number of iterations of MCT and LRT, the algorithm is stopped and the best pigeon at that time gives the optimal solution [8].

3.3.2. *Predator-Prey Optimization.* Predatory behavior is one of the most common behaviors of animal kingdom. Predators hunt prey for their own survival and control the prey population. In PPO, an individual in predator population or prey population is the solution. Predators try to kill prey with least fitness value in their vicinity and thus remove bad solutions.

3.3.3. *Predator-Prey Pigeon Inspired Optimization.* The PIO algorithm has the ability to trap into local optimal solution. This problem can be solved by combining PIO with PPO, which is called Predator-Prey PIO. PPO is used in this optimization technique to increase the diversity of the population. The cost function can be selected as follows:

$$J = \int_0^\infty \Big[k_1|e(t)| + k_2\tau_u^2(t) + k_3|e(t)|\Big]dt + k_4t_u$$

where, k_1, k_2, k_3, k_4 represent the weighted coefficients and $k_3 \gg k_1$. $e(t)$ represents the instantaneous error, $\tau_u(t)$ represents the output of the controller and t_u represents the rise time. k_3 is used to minimize overshoot, so $k_3 = 0$ if $e(t) > 0$ [10].

Every local PID controller is tuned by PPPIO and it can be written as

$$\tau_u = K_pe(t) + K_i\int_0^t e(t) + K_d\frac{d}{dx}e(t)$$

where, K_p, K_i and K_d are the parameters of the PID controller.

3.4. **T-S fuzzy global controller design.** After optimizing the parameters of each local controller, an optimized global controller is obtained via T-S fuzzy logic. The global parameters are used in a PID controller and therefore, it is able to control the actual nonlinear system efficiently. Finally, the nonlinear control system design is concluded.

The designing procedure of this controller is shown in Figure 3 and written below in a nutshell:

Step 1. First of all, the nonlinear model should be rewritten in the canonical state-space form.

Step 2. The model is linearized using T-S fuzzy linearization into local linear models.

Step 3. The control parameters K_p, K_i and K_d are optimized for a PID controller for each local model.

Step 4. The control parameters of the PID controllers for the local models are used to construct a fuzzy PID controller, which is able to control the actual nonlinear model.

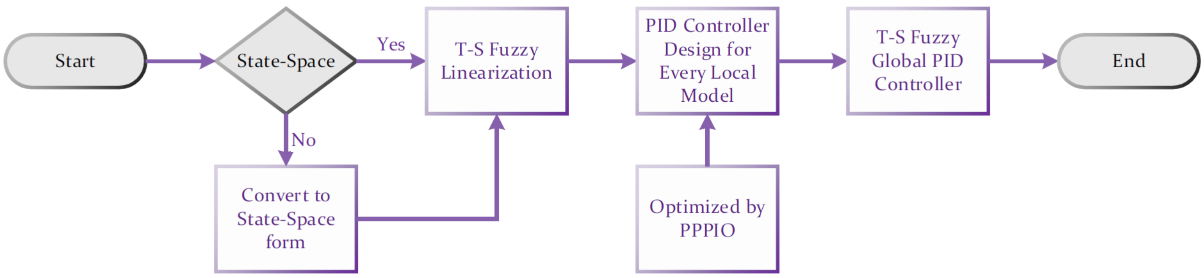

FIGURE 3. Flow chart of the proposed controller

4. **Simulation and Results.** In order to prove the effectiveness of this controller, simulation is performed in Simulink (MATLAB) at fixed speed set points for Cybership II. First of all, linearization points should be selected at equal intervals as 0.15, 0.30, 0.45 and 0.60 m/s. Then, the nonlinear surge model is linearized at these linearization points, which result in four linear models. For the optimization process, the number of pigeons is considered as 30 and total number of iteration as 100. Optimization is done by PPPIO for each linear model and the parameters K_p, K_i and K_d (with search spaces 0 to 30, 0 to 10 and 0 to 10, respectively) are obtained for each rule of the fuzzy controller. Finally, the parameters of all the local models are combined using T-S fuzzy logic to design the global controller.

A comparison of traditional PID and the proposed fuzzy PID controllers is performed and the results are shown in Figures 4 to 6 respectively for 0.1, 0.3 and 0.5 m/s. In these figures, the dashed line represents the normal PID controller which was tuned using the Simulink's inbuilt tuner and the solid line shows the response of the proposed controller. In Figure 4, the responses of both the controllers are almost the same with a slight difference in overshoot. However, as the surge speed increases, the overshoot of traditional controller

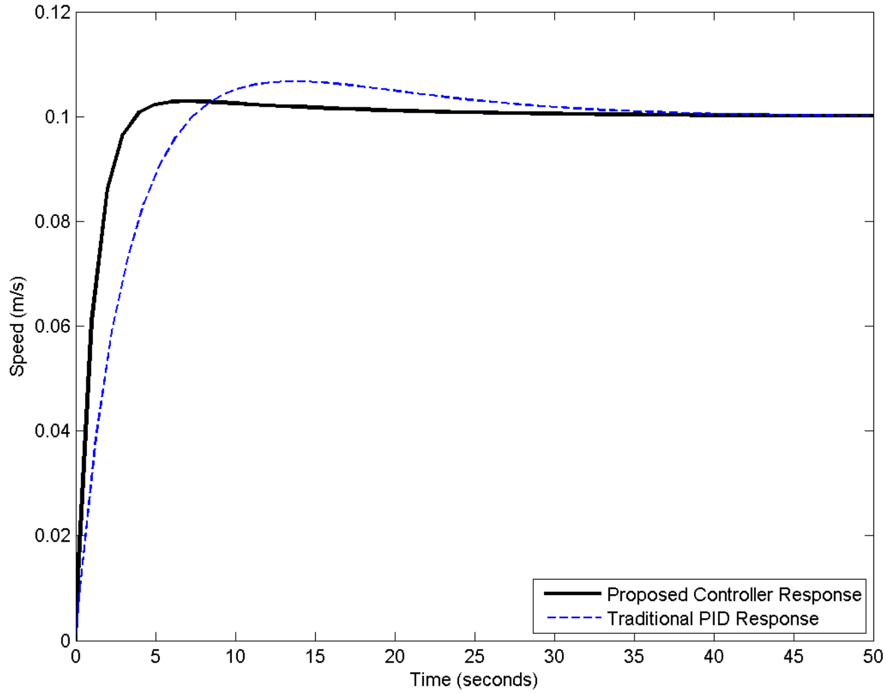

FIGURE 4. Comparison of traditional and proposed controllers at speed 0.1 m/s

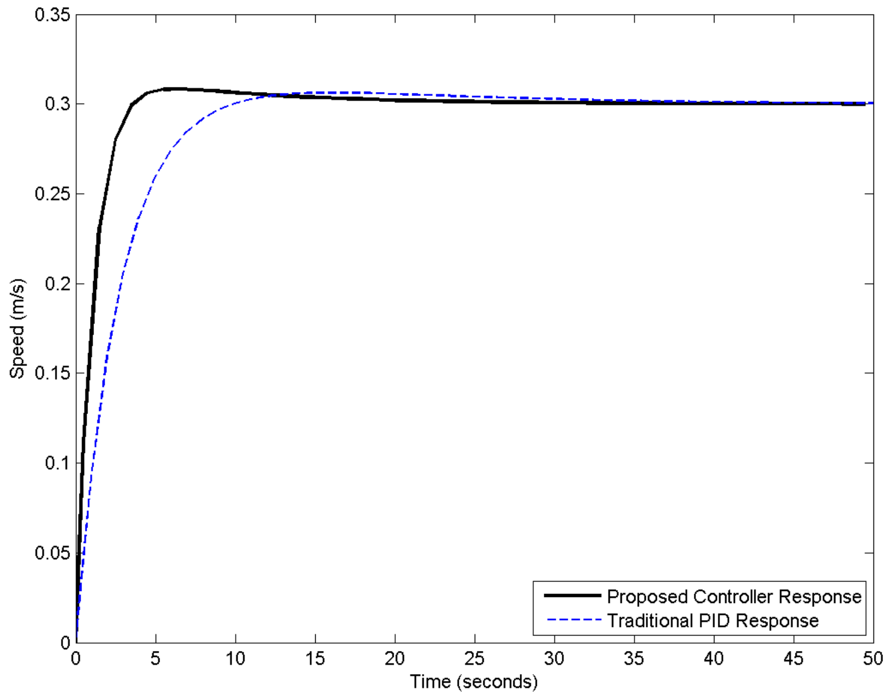

FIGURE 5. Comparison of traditional and proposed controllers at speed 0.3 m/s

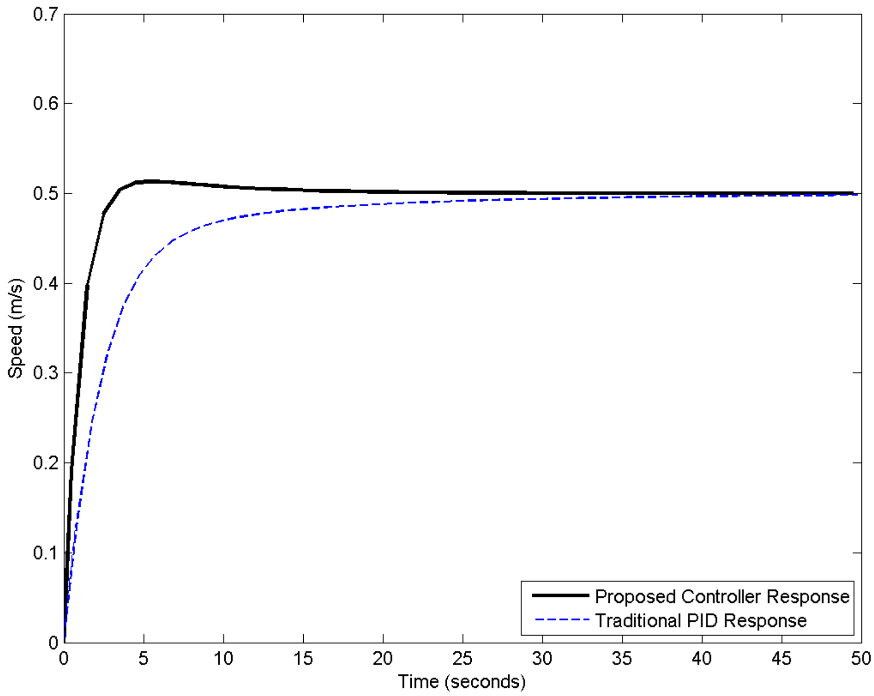

Figure 6. Comparison of traditional and proposed controllers at speed 0.5 m/s

decreases but rise time increases as shown in Figure 5, while the response of the proposed controller remains almost the same. From Figure 6 it can be observed that the rise and the settling times have also increased for the traditional controller due to increase in speed and thus nonlinearity and there is also an undershoot. However, this nonlinearity has not affected the proposed controller. These results suggest that the proposed controller has a good quality of control in both linear and nonlinear speed regions.

5. **Conclusions.** This paper presents a procedure to design a speed control system of a high speed ship and the actual parameters of Cybership II are used to ensure its effectiveness. The simulation results show that the proposed controller is much better for nonlinear systems and it gives good rise and settling time as compared to the traditional PID controller. In the future, this control system can be extended to more than one degree of freedom.

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