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Robust nonlinear PD controller for ship steering autopilot system based on particle swarm optimization technique

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ABSTRACT

This paper proposes a new approach for robust nonlinear proportional derivative (PD) controller. In this approach a nonlinear function (sigmoid) is added to the conventional proportional integral derivative (PID) controller with filtering for the derivative, in order to improve system response and to reduce the effects of the nonlinearity and uncertainty due to variations of hydrodynamic coefficients of ship with the speed. The gains of nonlinear PD controller are tuned by applying particle swarm optimization (PSO) technique. The simulated results by MATLAB program give satisfactory performance with regard to maximum overshoot, settling time and zero steady state error for step, ramp and proposed trajectory as input to the system. The robustness of the autopilot was checked by changing the plant parameters and adding disturbance to the plant input. The used autopilot is nonlinear PD controller because the gain of integral term by PSO is approximately zero which simplifies the controller construction. The results show that the proposed controller has superior transient response and robustness on the conventional PID designed by using symmetrical optimum criterion with pole assignment technique.

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1. INTRODUCTION

The PID controllers are most popular controllers and widely used in industry applications even though many new control techniques have been proposed because of simplicity of implementation and small improvement in the controller design can give large improvement in the system response [1-2]. Accurate tuning of PID controller is necessary for maintaining the desired performance. There are many tuning algorithms used in order to obtain accurate gains for PID controller. Many of tuning processes are manually implemented. Manually tuning processes are difficult in addition to time consuming. Now widely used techniques for tuning PID parameters are soft computing techniques. PSO method used to search efficiently for the optimal PID controller parameters [3-4].

The ship model has uncertain parameters, caused by the variations of hydrodynamic coefficients due operational conditions such that speed changes, ballast condition, trim, and water depth. The most important external disturbances are waves generated by the wind and ocean current. Autopilot using quantitative feedback theory (QFT) was designed to obtain the robust stability, tracking response and disturbance rejection conditions [5-6]. For high performance ship autopilot in the presence of nonlinearity and disturbance, sliding mode controller is proposed [7]. An adaptive sliding mode control method and nonlinear disturbance observer are proposed for ship autopilot to provide robust response in the presence of main disturbance [8]. A sliding mode with fuzzy gain scheme was present for ship autopilot [9-10]. An expert system was designed to stabilize the autopilot [11]. A hardware PID microcontroller was implemented for rudder control [12]. The conventional PI controller combines with fuzzy PD controller was proposed for ship autopilot to improve the steady state error and to reduce rise time and overshoot [13]. Proportional–integral–derivative (PID) controller combined with fuzzy logic for small-scale wind turbine systems [14]. A fuzzy controller with linear PID controllers for ship steering was proposed to get small overshoot and settling time [15]. The PID controller introduced for autonomous vehicle steering controller to improve the convergence of the steering to control the Motor direction and perform the calculation of the desired steering angle [16]. Fractional-order proportional integral derivative (FOPID) controller Proposes as a speed controller for permanent magnet direct current (PMDC) motor, instead of the traditional integer-order PID controller [17-18]. A recursive least square (RLS) algorithm, with rate limiters, is implemented to perform an online self-adjusting of each of the PID gains in order to achieve adaptive PID (APID) controller that will accommodate to system variations [19]. To improve the performance of the overall system, methods of artificial intelligence techniques for designing the optimal values of PID controller is used [20]. The robust control schemes such as the sliding mode control method utilized in the ship steering control to achieve better ship course keeping and changing maneuver [21-22]. PID controller tuned by Beetle Antennae Search optimization method proposed ship autopilot [23]. Process is nonlinear and has variety of uncertainties due to the effective factors that make it difficult to choose the parameters of the model. The PID controller is used to assure zero steady state error for both step and ramp variations on command and disturbances inputs for yaw angle of autopilot ship. In this work the parameters of PID controller with nonlinear element (sigmoid function) are tuned using PSO method. This work focused on reducing the overshoot and settling time in addition to improve the robustness of the system.

2. PID CONTROLLER

The proposed PID controller is used to improve the transient and steady state response for the dynamic system. The transfer function of conventional PID controller with filtering for derivative part is given by:

$$G_{PID}(s) = k_p + \frac{k_i}{s} + k_d s \frac{N}{S+N} \tag{1}$$

Wherek_p,k_i,k_d and N are the proportional, integral, derivative and filter gains respectively. The nonlinear PID controller is obtained by adding a sigmoid function to the conventional PID controller in (1). The control input (u) for the plant will become:

$$u = \frac{2}{1+e^{-\lambda x}} - 1 \tag{2}$$

Where λ is the gain of sigmoid function and x is the output of conventional PID [24]. The structure of nonlinear PID controller is shown in Figure 1.

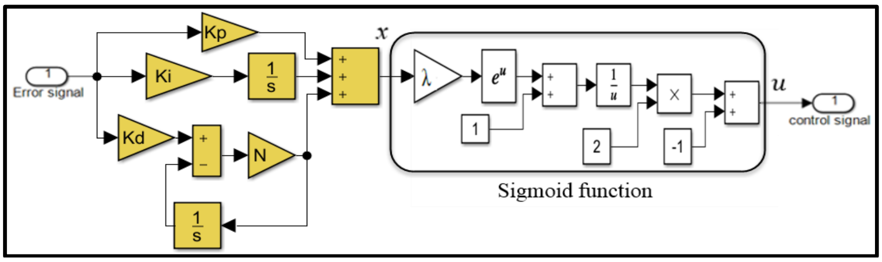

Figure 1. Structure of the nonlinear PID controller

3. LINEARIZED MODEL OF SHIP STEERING CONTROL SYSTEM

The traditional autopilot system usually uses a proportional-derivative (PD) controller, which has constant parameters for proportional and derivative coefficients. But the quality of PD control is deteriorated when there are changes in speed, weight, and so on, of the ship or there are external disturbances. Therefore, there is a need for designing a robust control system that means a control system in which the quality of control doesn't degrade even if some parameters of the ship change [25-26]. The control system is designed for ship steering to perform two different functions course-keeping and course-changing maneuvers [27-28]. The ship dynamics modeling for characterizing a slow process can be derived from the equations of the horizontal motion for the ship. The ship yaw angle (ψ) is the model output, and rudder command (δ) generated by autopilot is the control input. The linear model of the ship's dynamics for yaw motion, without considering any perturbations, can be represented as a first order Nomoto model. The identified model for a ship is given by:

$$\ddot{\Psi}(t) + \frac{1}{T_P}\dot{\Psi}(t) = \frac{k_P}{T_P}\delta(t) \tag{3}$$

$$H_P(s) = \frac{\psi(s)}{\delta(s)} = \frac{k_P}{s(sT_P+1)} \tag{4}$$

where $\psi(s)$ and $\delta(s)$ represent the Laplace transforms of yaw angle and rudder angle respectively and the parameters T_P and k_P regard to operating conditions for example load, speed, water depth, etc. [1]. For large maneuvers, the nonlinear ship models must be taken into account. The nonlinear term must be added to Nomoto equation, resulting Norrbin model which can be represented in the following form [5]:

$$\ddot{\Psi}(t) + \frac{1}{T_P}\dot{\Psi}(t) + \frac{1}{\mathrm{T_P}}\mathrm{m}\dot{\Psi}^3 = \frac{k_P}{T_P}\delta(t) \tag{5}$$

Where m is the coefficient of the nonlinear term. In this work, small changes of the yaw angle are assumed so the nonlinear term in (5) is very small therefore the linear model in (4) can be used. The parameters for a linear model with a speed of 22 knots are [1]:

$k_P = -\,0.0834$ (s^{-1}), $T_P = 5.98$ (s).

4. PARTICLE SWARM OPTIMIZATION TECHNIQUE

The well-known equations of PSO algorithm is given by [2]:

$$V_{i,j}^{(k+1)} = w * V_{i,j}^{(k)} + c1 * r_1 * \left(\mathrm{Pbest}_i - X_{i,j}^{(k)}\right) + c2 * r_2 * \left(\mathrm{Gbest}_i - X_{i,j}^{(k)}\right) \tag{6}$$

$$X_{i,j}^{(k+1)} = X_{i,j}^{(k)} + V_{i,j}^{(k+1)} \tag{7}$$

i = 1, 2… n: j = 1, 2… d;

Where n is the particle number, d is the number of variables, k is the iteration number, $\mathrm{V}_{\mathrm{I,j}}^{(\mathrm{k})}$ is the velocity of i^{th} particles at iteration k, $\mathrm{X}_{\mathrm{I,j}}^{(\mathrm{k})}$ is the position of i^{th} particles at iteration k, X^{k+1}= modified position, V^{k+1}= modified velocity, Pbest_i is the best position of i^{th} particles Gbest_i is the best particles of the population. And w is the weight factor, c_1, c_2 are constants, r_1, r_2 is an arbitrary number.

5. TUNING GAINS OF THE NONLINEAR PID CONTROLLER

Nonlinear PID controller gains tuning algorithm can be done by using closed loop system where the tuned parameters (k_p, k_i, k_d, λ and N) are tuned by reducing the error, which is the difference between the system response and desired response. The error can be minimized by using fitness function. The tuning procedure by PSO algorithm is illustrated in Figure 2.

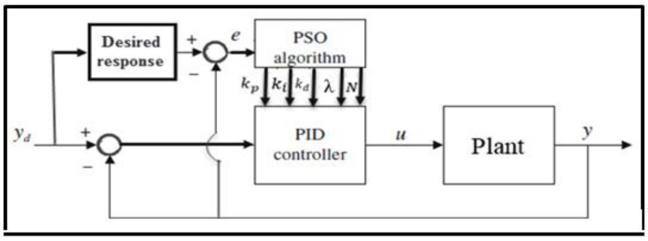

Figure 2. A diagram to adjust the PID controller by the PSO algorithm

The used fitness in this work is integral time square error

$$F_{ITSE} = \int_0^T t\, e^2(t)\, dt \tag{8}$$

The error e for fitness function is obtained from difference between the system response and desired response. The desired response is deduced from desired model. The desired model is selected according to the rise time of open loop transfer function (Hp (s)) for step input and adequate damping ratio (ζ=0.9). The Desired model is:

$$G_{desired}(s) = \frac{0.09}{s^2+0.54s+.09} \tag{9}$$

After running PSO program with c1=c2 =1.2, w=0.6, n= 12 and 50 iterations, the obtained nonlinear controller gains are K_P=34, K_i=0.0001, K_d=55, λ= -13.993, N=1.45. Because the gain k_i approached zero so the integral term will be neglected and the PID controller will be PD controller.

6. SIMULATION AND RESULTS

The proposed nonlinear PD controller and conventional PID controller are considered in this work. The simulation carried out for ship autopilot yaw angle with conventional PID controller taken from reference [1]. The main objective of the ship autopilot is to command the steering machine, so that the ship tracks a desired trajectory (route), which can be specified by way-points. The trajectory can be simulated by using both step and ramp inputs. To examine the robustness of the controller this can be handled produce the region of uncertainty and adding disturbances. The region of uncertainty can be simulated by two methods. The first method is by variations ±20%, ±40% and 100% on plant parameters ($k_p$and T_p) and the second method is by changing parameters in two value ranges: [$k_p$minimum, $k_p$maximum] and [$T_p$minimum, $T_p$maximum]. The step response using nonlinear PD controller is shown in Figure 3, which has approximately the same as desired response. Also step response using conventional PID controller with and without saturation for the control signal u is shown in Figure 3. Saturation is used to simulate the possible u.

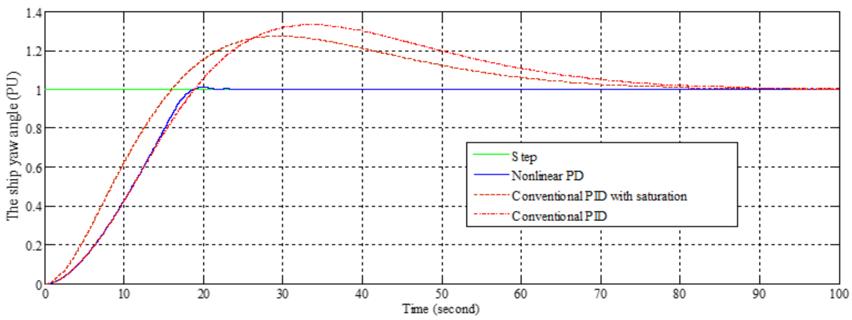

Figure 3. Step input response using nonlinear PD and conventional controller

Figure 3 shows that output response using nonlinear PD controller track the reference input better than using conventional PID controller. The step responses of the controlled system using nonlinear PD controller with variation of plant parameter of ±20%, ±40% and 100% (first method for robustness test) shown in Figure 4.

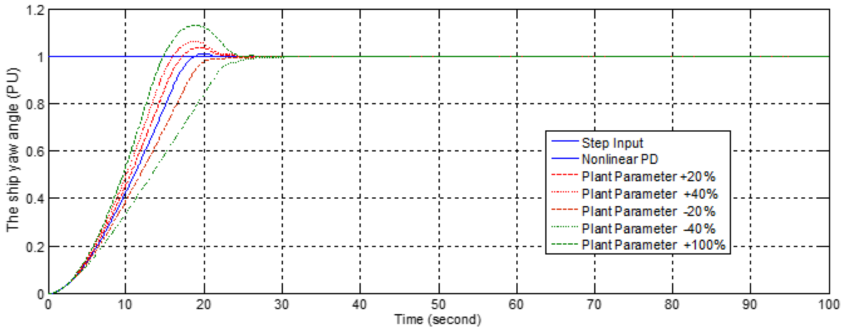

Figure 4. Step responses of the system using nonlinear PD controller

From Figure 4 it is clearly noticed that the response of nonlinear PD controller with variation of plant parameters is better than the response of conventional PID controller without variation of plant parameters. The ramp responses of the controlled system using nonlinear PD and conventional PID controllers are shown in Figure 5. Figure 5 illustrate that the nonlinear PD controller response track reference input with zero steady state error faster than the response of conventional PID controller.

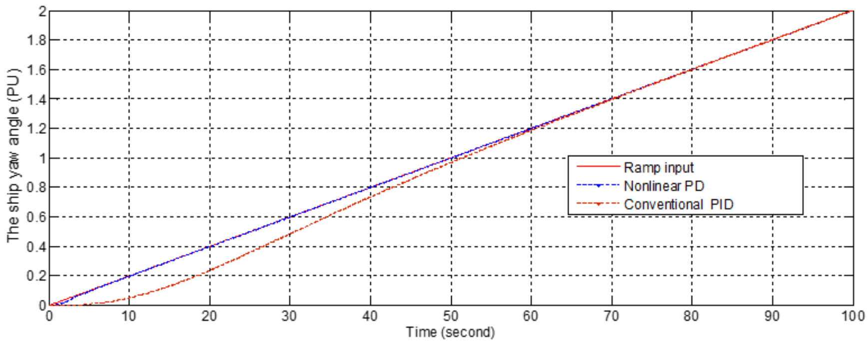

Figure 5. Ramp responses for controlled system using nonlinear PD and conventional PID controller

Ramp responses for ship yaw angle using nonlinear PD controller with ±20%, ±40% and 100% variation on the plant parameters according to first method are shown in Figure 6 and shows that the response of nonlinear PD with plant parameter variation is better than the conventional PID controller without plant parameter variation, as depicted in Figure 5.

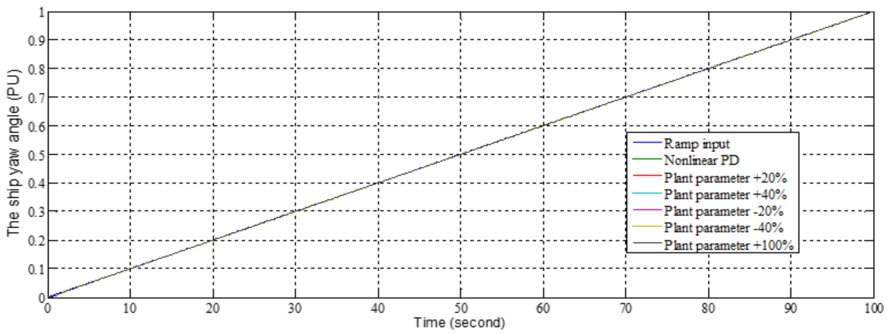

Figure 6. Ramp responses of nonlinear PD controller with variation of plant parameters

The step responses of the controlled system using nonlinear controller with the variation of plant parameter by [3]: $kp \in [-0.03, -0.1,]$ and $Tp \in [1.7,12]$ (second method for robustness test) are shown in Figure 7.

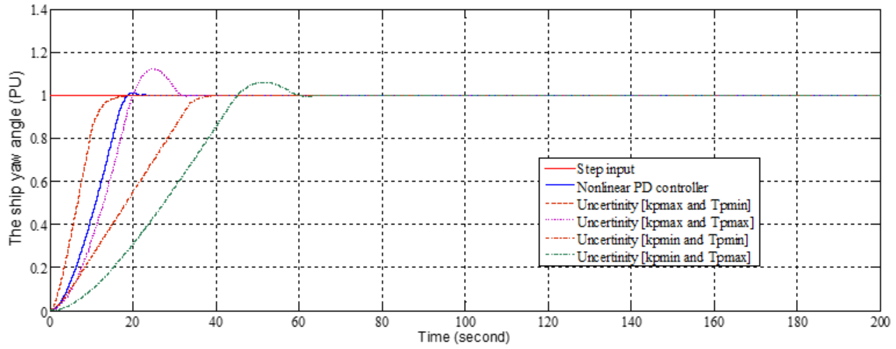

Figure 7. Step responses using nonlinear PD controller with variation of plant parameters

Figure 7 depicted that the nonlinear PD is better than the conventional PID controller without variation of plant parameter. So, the robustness of the nonlinear PD is better than the conventional PID controller. The responses for proposed trajectory using both controllers are illustrated in Figure 8.

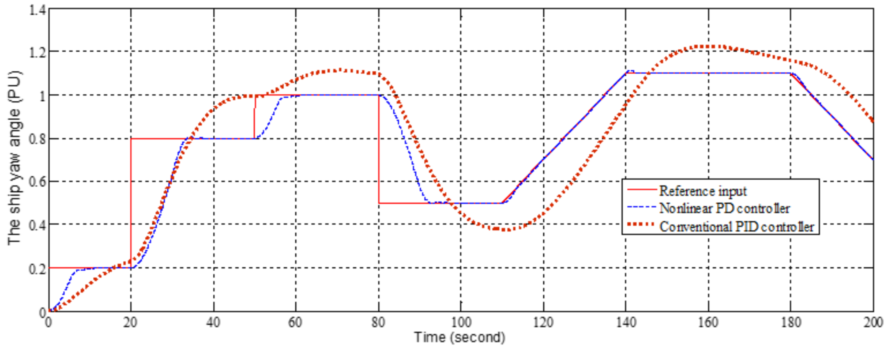

Figure 8. Trajectory responses for ship using conventional and nonlinear PD controller

Figure 8 depicted that the response using the nonlinear PD controller track the reference input better than the response using conventional PID controller. To study the effect of the actual disturbance generated from the wind or waves of the sea or by the system itself, additive random noise to the control signal *u* generated by the controller is proposed. The propose disturbance shown in Figure 9. The effect of disturbance input to the plant using nonlinear PD controller for step input is very smallas shown in Figure 10.

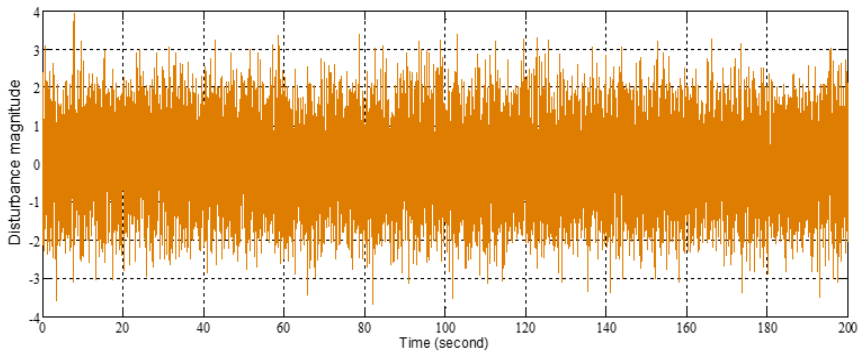

Figure 9. The proposed disturbance input to the plant

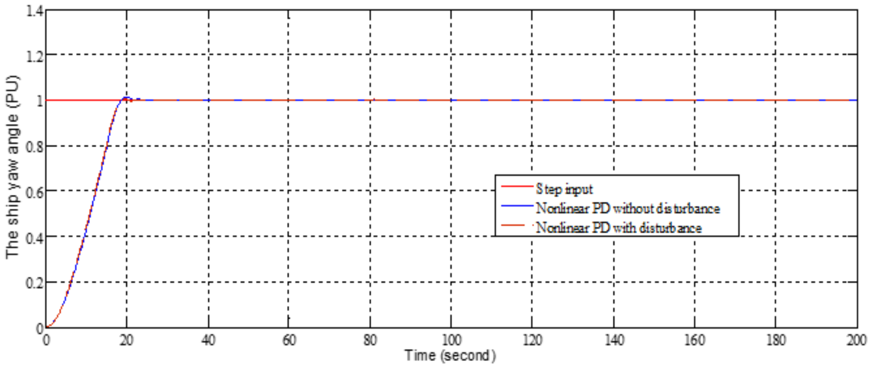

Figure 10. Step response for the system using the nonlinear PD controller with disturbance

7. CONCLUSION

Mathematical model of ship is uncertain and nonlinear. The source of uncertainty is the variations of hydrodynamic coefficients due operational conditions. Autopilot is designed to maintain the ship on a set course and provides good manoeuvrability. The ship model has an unstable open loop transfer function. New nonlinear PD controller is proposed to reduce the effect of uncertainty and stabilizes the open loop system response. New nonlinear PD controller is suggested by adding a nonlinear function to conventional PID controller. The PSO can be used to find the optimal gains of nonlinear PID controller. The used controller is nonlinear PD controller because obtained gain of integral term by PSO is approximately zero. The simulation results show that the proposed controller is more efficient in viewpoint of transient response and robustness than conventional PID controller designed by using symmetrical optimum criterion with pole assignment technique. The proposed nonlinear PD controller is superior on the conventional PID to control uncertain, nonlinear and unstable plant.

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