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Optimized PID Controller for Magnetic Levitation System

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Abstract: In this paper, an optimized proportional-integral-derivative (PID) controller is designed to control the ball position of the magnetic levitation system (MLS). The electromagnetic force of the MLS is controlled by sensing the position of the ball with the help of the infra-red (IR) sensors. The system performance is improved in terms of time & frequency domain by optimizing the parameters of the PID controller using grey wolf optimizer (GWO). The GWO algorithm tunes the parameter of the PID controller while minimising the performance index of the system such as integral time weighted absolute error (ITAE) and integral time weighted square error (ITSE). The effectiveness of the proposed controller is validated by comparing it with the classical tuning criterion.

Keywords: Magnetic levitation system, PID controller, Grey wolf optimizer.

1. INTRODUCTION

Magnetic levitation systems have been widely used in magnetic bearings, high-speed trains, vibration isolation of sensitive machinery, levitation of wind tunnel models, etc., C. R. Knospe and E. G. Collins (1996). Several magnetic suspension systems have been developed and applied for magnetically levitated transit systems in recent years, has been investigated by Rule R. et al. (1980) and Ion B et al. (1988). Maglev systems are inherently nonlinear, unstable and are described by highly nonlinear differential equations which present additional difficulties in controlling these systems. So the design of feedback controller for regulating the position of the levitated object is always a challenging task is presented by Vinodh Kumar et al. (2013). In most cases the control system and energy supply requirements to levitate the object have a higher level of complexity. The nonlinear nature of the systems dynamics coupled with the nonlinear characteristics of the actuators complicate the controller design was consider by Marjan Golob et al. (2003). For such a system it is desired to propose a suitable controller for positioning a ball in the air space with the help of an electromagnetic force. In the ideal situation, the magnetic force produced by the current from an electromagnet counteracts the weight of the metal ball. However, the electromagnetic force is very sensitive, and there is noise that creates acceleration forces on the ball, causing the ball to move into the unbalanced region, Yadav et al. (2012).

In this paper, the metal ball is balanced in the air-space by controlling the electromagnetic force of the MLS using PID controller because more than 90% of the industrial controllers are still implemented based around the PID algorithms due to its simplicity, ease of implementation and robustness. The PID controller is a combination of the PI and PD controllers. It is similar to lag-lead compensator. The PI control action and PD control action occur in low and high frequency regions. The PID control is used when the system performance requires improvement in both the transient and steady-state performance. The parameters of PID controller are tuned using classical tuning criterion such as Ziegler-Nichols (Z-N) tuning rules. The Z-N rules give an educated guess for the parameter values and provide a starting point for fine tuning, rather than giving the final settings points for the PID controller, Katsuhiko Ogata (2009). To improve the transient performance of the system, these tuned parameters are optimized.

S. Mirjalili, S. M. Mirjalili, and A. Lewis (2014) introduces a new meta-heuristic evolutionary algorithm known as Grey wolf optimizer (GWO) is used to optimize the parameters of the PID controller. The GWO algorithm searches for the optimum solution in the desired range space by updating the position of the wolves depending on the location of the prey, the concept given by Seyedali Mirjalili (2015). The GWO algorithm is capable of maintaining the balance between the exploration and the exploitation properties of the search space. The grey wolves strictly follow the social hierarchy as they are categorised in to four different groups namely, alpha (α) the leader, beta (β) assist alpha during the hunting process, delta (δ) act as a subordinate and omega (ω) the followers, S. Saremi, S. Z. Mirjalili, and S. M. Mirjalili (2014). The proposed algorithm tunes the parameters of the PID controller focuses on minimising the integral square error of the MLS. As the error of the system decreases, the desired time domain specifications are achieved to meet the system requirements. The performance of the PID controller is validated by analyzing the frequency plots. The metal ball of the MLS is levitated in the air-space within fraction of seconds. However, the system performance when the parameters are optimized using GWO algorithm is over-damped, which is acceptable for some types of problems like, elevator, liquid level in water tank and etc. The simulation and experimental result shows the effectiveness of the proposed controller, which advances the system performance as compared with the classical tuning approach.

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The organization of this paper is as follows. In Section 2, Description of magnetic levitation system is presented. In Section 3, the PID control technique is discussed. Section 4 presents the GWO algorithm. Section 5 covers results and discussion. Section 6 presents the Conclusion and finally the references.

2. DESCRIPTION OF MAGNETIC LEVITATION SYSTEM

The MLS comprises of an electromagnet coil, a metal ball and an IR position sensor. The metal ball sensed by an IR sensor separate the vertical movement of the ball from the horizontal one. The minimum and the maximum distance of the ball from the electromagnetic coil are 0.5 cm to 0.25 cm. The MLS can be decomposed into two subsystems, viz., a mechanical system and an electrical system. The ball position in the mechanical system can be controlled by adjusting the current through the electromagnet whereas the current in the electrical system can be controlled by applying controlled voltage across the electromagnet terminals. Thus, the voltage applied across the electromagnet terminals provides an indirect control of the ball position has been discussed by C. R. Knospe and E. G. Collins (1996).

The nonlinear model of the MLS is derived by using the fundamental principle of dynamics. The behaviour of the metal ball is given by the following electromechanical equation:

$$m_B \ddot{x}_B = m_B g - f(x_B, i_c) \tag{1}$$

where $\mathrm{f}(\mathrm{x_B}, \mathrm{i_c}) = \mathrm{k}\frac{\mathrm{i_c^2}}{\mathrm{x_B^2}}$ is the magnetic control force, $\mathrm{m_B}$ is the mass of the ball $(20 \times 10^{-3}\ \mathrm{kg})$, g denotes the gravitational constant $(9.81\ \mathrm{m/s^2})$, k is a constant related to the mutual inductance of the ball and the coupling coefficient, $\mathrm{i_c}$ is the coil current and $\mathrm{x_B}$ is the distance of the ball from the electromagnet. To levitate the ball in the air-space, the MLS should be linearized, as techniques like root-locus, bode plot, pole-zero map and Nyquist plots are not feasible for the nonlinear systems. The MLS is linearized by taking the approximates of $\mathrm{x_B}$ and $\mathrm{i_c}$as

$$x_B = \bar{x}_B + \tilde{x}_B \tag{2}$$

$$i_c = \bar{\imath}_c + \tilde{\imath}_c \tag{3}$$

where $\bar{x}_B$ and $\bar{\imath}_c$ are the value at the operating point, $\tilde{x}_B$ and $\tilde{\imath}_c$ shows the variations around the operating point. If we assume that $\bar{x}_B \gg \tilde{x}_B$ and $\bar{\imath}_c \gg \tilde{\imath}_c$and using Taylor's series expansion gives:

$$f(x_B, i_c) = k\frac{\bar{\imath}_c{}^2}{\bar{x}_B{}^2} + \left(\left.\frac{\partial f(x_B, i_c)}{\partial i_c}\right|_{\bar{\imath}_c, \bar{x}_B} \bar{\imath}_c + \left.\frac{\partial f(x_B, i_c)}{\partial x_B}\right|_{\bar{\imath}_c, \bar{x}_B} \bar{x}_B \right) \tag{4}$$

From the above equation, the higher order terms are neglected and the first order approximation is chosen. The partial differential terms can be solved as:

$$\left.\frac{\partial f(x_B, i_c)}{\partial i_c}\right|_{\bar{\imath}_c, \bar{x}_B} = -2g/\bar{\imath}_c = -k_1 \tag{5}$$

$$\left.\frac{\partial f(x_B, i_c)}{\partial x_B}\right|_{\bar{\imath}_c, \bar{x}_B} = 2g/\bar{x}_B = k_2 \tag{6}$$

Substituting equation (5) and (6) in to equation (1)

$$m_B \ddot{\tilde{x}}_B = m_B g - k\frac{\bar{\imath}_c{}^2}{\bar{x}_B{}^2} - k_1 \tilde{\imath}_c + k_2 \tilde{x}_B \tag{7}$$

By defining the equilibrium point at $\bar{x}_B = -1.5$ volt, $\bar{\imath}_c = 0.8$ A, the point where there is no acceleration and the incremental terms are equal to zero i.e.,

$$\mathrm{m_B g} - \mathrm{k}\frac{\bar{\imath}_c{}^2}{\bar{x}_B{}^2} = 0$$

The equation of motion takes the form of:

$$\ddot{\tilde{x}}_B = \frac{1}{m_B}(k_2 \tilde{x}_B - k_1 \tilde{\imath}_c) \tag{8}$$

Take the Laplace transform of equation (8), gives-

$$\frac{\tilde{x}_B(s)}{\tilde{\imath}_c(s)} = \frac{-K_1}{m_B s^2 - K_2} \tag{9}$$

The open-loop transfer function of the MLS is a second order system with complex conjugate poles for any value of the metal ball. The closed-loop response of the MLS is oscillatory in nature i.e., either the metal ball attracted towards the electromagnetic coil or it may be fallen down. Therefore, there is a requirement of a controller which can effectively achieve the desired performances.

3. PID CONTROLLER

A continuous time PID controller is very popular since 1900 era, as one of the earliest examples of a PID-type controller was developed by Elmer Sperry in 1911. Around 90% of the industrial problems are handled by the PID controllers. It is commonly considered as an extreme form of a phase lead-lag compensator with one pole at the origin and the other at infinity is discussed by Kiam Heong Ang and Gregory Chong (2005). The transfer function of the PID controller is given by:

$$U_{PID}(s) = \left(K_P + K_I \frac{1}{s} + K_D s\right) E(s) \tag{10}$$

where K_P is the proportional gain, K_I is the integral gain, $K_D$is the derivative gain, E is the error of the system and U_{PID} is controller output. To find out the starting point of the PID controller, the parameters are tuned using ZN method due to its popularity and capability of providing the best result as compared with the other classical tuning criterion.

4. GREY WOLF OPTIMIZER

A Grey wolf (Canis lupus) optimizer is an evolutionary algorithm belongs to a Canidae family discussed by Muro C, Escobedo R, Spector L and Coppinger R (2011). The grey wolf searches for the prey (food) in a group size of 5-12 wolves. The grey wolves strictly follow the social hierarchy and share the top level of hierarchy depending on its dominating behaviour. The top level represents the dominating level of the hierarchy, and the one who belongs to this level is known as the leader denoted as alpha (α). The second level of the hierarchy is being shared by the wolf who assist α during the hunting process commonly known as beta (β). The third level of hierarchy is being shared by delta (δ) wolf, which act as a subordinate. The last level is the least dominating level of the hierarchy and the wolves who represent this level are the followers known as omega (ω) . The exploration property is preserved by splitting the searching criterion into three different directions is included by Emary, E., et al. (2015). The GWO algorithm comprises of following steps:

A. Encircling the Prey

The grey wolves encircle the prey by updating their position with respect to the top level of the hierarchy.

$$D = |C.X_P(t) - X(t)| \tag{11}$$

$$X(t+1) = X_P(t) - A.D \tag{12}$$

$$A = 2a.r_1 - a \tag{13}$$

$$C = 2.r_2 \tag{14}$$

where A and C are coefficient vectors, X_P is the position vector of the prey, X indicates the position vector of the grey wolf, t is the current iteration, r_1 and r_2 are the random values lie in the range [0, 1].

B. Hunting Behaviour

The wolves which provides the best solutions were considered as α, β, and δ. The positions of the other wolves are reorganized with the correspondence to these three wolves as:

$$\left.\begin{aligned} D_{\alpha_i} &= \left|C_1.X_{\alpha_i}(t) - X_i(t)\right| \\ D_{\beta_i} &= \left|C_2.X_{\beta_i}(t) - X_i(t)\right| \\ D_{\delta_i} &= \left|C_3.X_{\delta_i}(t) - X_i(t)\right| \end{aligned}\right\} \tag{15}$$

$$\left.\begin{aligned} X_{i1} &= X_{\alpha_i}(t) - A_1.D_{\alpha_i} \\ X_{i2} &= X_{\beta_i}(t) - A_2.D_{\beta_i} \\ X_{i3} &= X_{\delta_i}(t) - A_3.D_{\delta_i} \end{aligned}\right\} \tag{16}$$

$$X_i(t+1) = \frac{X_{i1}+X_{i2}+X_{i3}}{3} \tag{17}$$

where i is the no. of iterations and $X_i(t+1)$ is the best search agent for the iteration i.

C. Attacking Prey

To reduce the gap between the position of the grey wolves and the location of the prey, the coefficient vector A is decreased. As the mean of the performance index minimizes, the value of vector A is decreased as

$$a = 2 - \left(\frac{2}{max.iter_i}\right) \tag{18}$$

where $max.iter_i$ is the maximum value of the performance index at iteration i, a is decreased from 2 to 0 as the no. of iteration increases.

5. RESULTS & DISCUSSION

In this paper, a PID controller is designed for MLS to levitate the metal ball in the air-space. The MLS consists of electromagnetic coil, mounted on top of the box. The IR sensor is fixed on opposite sides of the box, so that it may easily sense the position of the metal ball. The metal ball gets attracted when it is near to the electromagnetic coil and otherwise fallen down due to the gravitational force. The purpose of the PID controller is to maintain an equivalent electromagnetic force, so that the metal ball is levitated. The closed-loop poles of the MLS are locates at $s = \pm j43.3590$. The step response of the MLS is undamped and therefore, to control such an oscillatory system, the controller should be fast and capable of improving the design requirements such as:

1. Maximum Overshoot $\leq 15\%$
2. Settling Time $\leq 1\ sec.$

The parameters of the PID controller are obtained using the PID tool of MATLAB and tuned by Z-N tuning rule. The PID controller improves the settling time of the system but unable to obtain the desired overshoot as shown in Table 1. The step response of the MLS with PID controller is shown in Fig. 1.

Table 1. Performance Characteristics with PID controller

Proportional Gain K_P	**Integral Gain K_I**	**Derivative Gain K_D**	**Settling Time (t_s)**	**Max. Overshoot**
9.4085	19.8483	0.05730	0.5030	37.6922

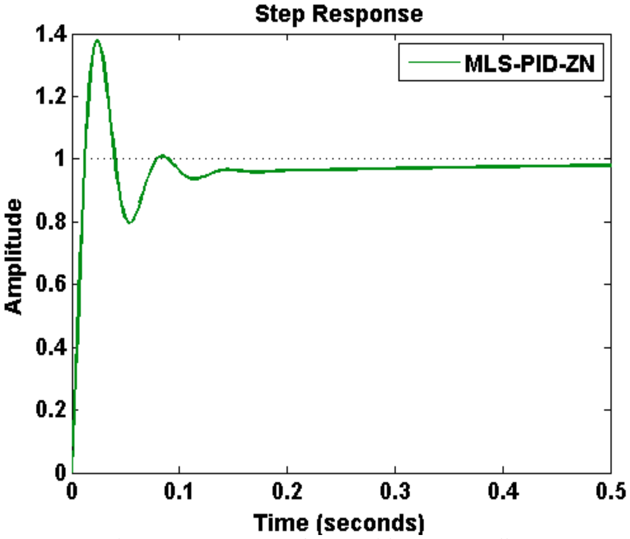

Fig. 1. Step response of MLS with PID controller

The comparison of closed-loop step response of MLS with and without PID controller is not possible because the original system is oscillatory. To show the effectiveness of the PID controller, the frequency plot are analysed as shown in Fig. 2.

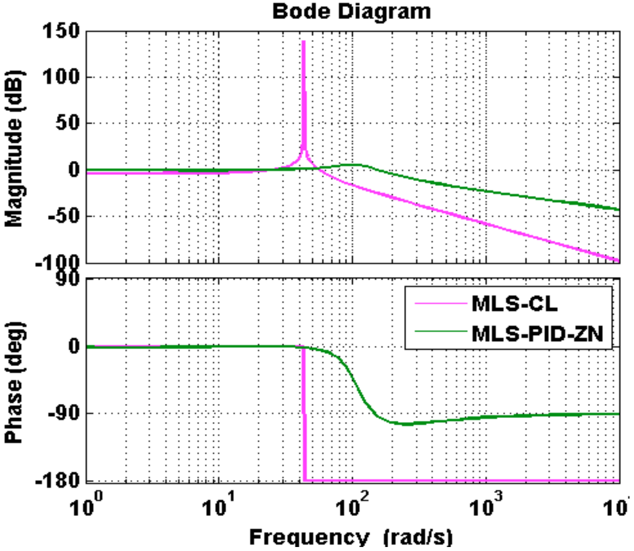

Fig. 2. Bode plot of MLS with and without controller

To meet all the design requirements the parameters of the PID controller are optimized using GWO algorithm. The GWO algorithm optimizes the parameters of the PID controller while minimizing the performance indices like ITAE and ITSE.

$$J_{ITAE} = \int_0^{\infty} t.|e(t)|\,dt \tag{19}$$

$$J_{ITSE} = \int_0^{\infty} t.e^2(t)\,dt \tag{20}$$

The search space for the GWO algorithm is selected on the basis of the parameters tuned using Z-N rule and it will act as a leader for the first iteration. The other wolves are selected randomly around alpha by a suitable guess. The search space should be defined properly to obtain a global optimum solution. The range for the parameters of PID controller is defined as follows: $(1 \le K_P \le 350)$, $(0.01 \le K_I \le 300)$ and $(0.0001 \le K_D \le 200)$. The optimized parameters of PID controller are obtained by searching for the global optimum solution for around 500 of iterations. The comparison of step response of the MLS with PID controller tuned using GWO and Z-N tuning rule is shown in Fig. 3.

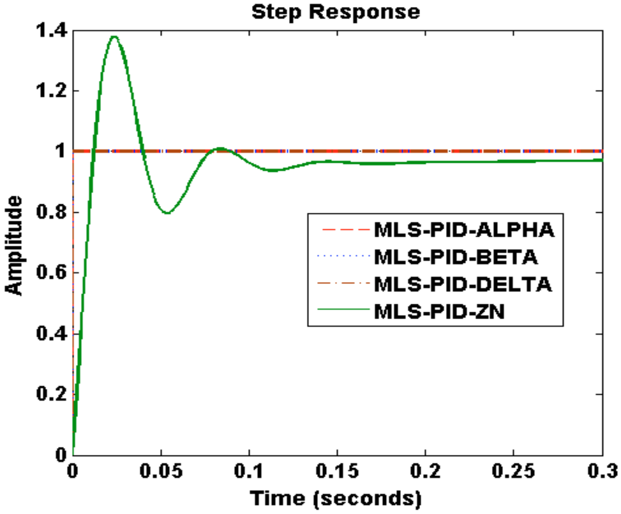

Fig. 3. Step response of MLS with PID tuned using GWO & Z-N rule

As the settling time of the system is very fast therefore, responses of alpha, beta and delta are shown in Fig. 4.

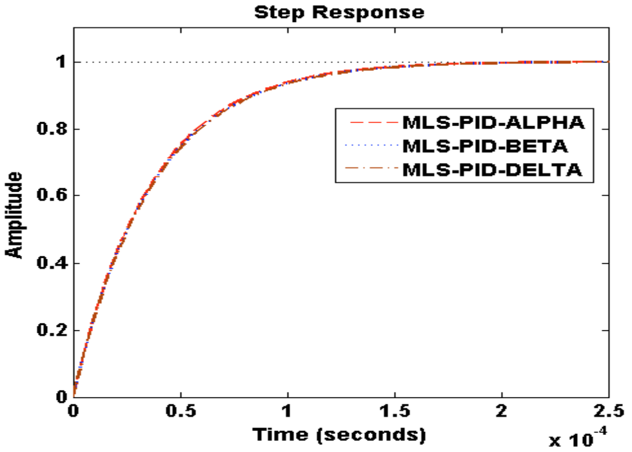

Fig. 4. Step response of MLS with PID tuned using GWO

The bode plot shown in Fig. 5 to compare both the tuning criterion. The bode response validate the effectiveness of the GWO algorithm. The parameters of PID controller optimized using GWO algorithm is shown in Table 2.

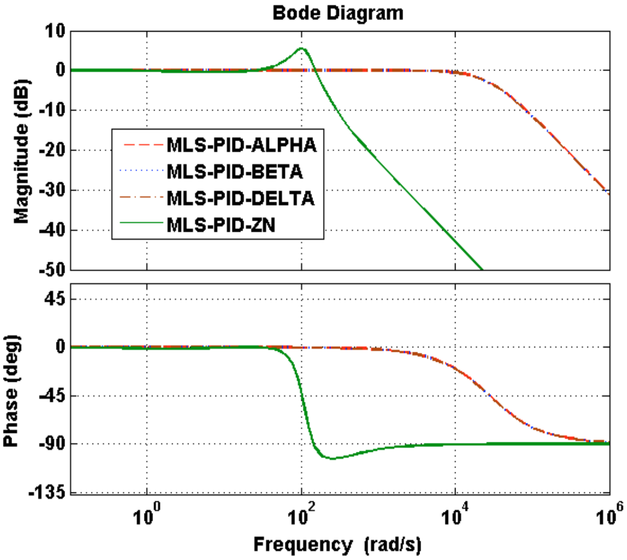

Fig. 5. Bode plot of MLS with PID tuned using GWO & Z-N rule

Table 2. Parameters optimized using GWO algorithm

Grey wolves	K_P	K_I	K_D
α	222.8579	181.8144	33.9586
β	290.0806	236.6568	44.2018
δ	173.7181	141.7246	26.4708
ω_1	242.4454	197.7945	36.9433
ω_2	278.2969	227.0433	42.4063
ω_3	158.9236	129.6548	24.2164
ω_4	278.2673	227.0191	42.4017
ω_5	260.6799	212.6708	39.7218
ω_6	316.2232	257.9847	48.1854
ω_7	54.9622	44.8399	8.3750
ω_8	224.2803	182.9749	34.1753
ω_9	190.9889	155.8147	29.1025

The performance characteristics of MLS with GWO algorithm in terms of time domain specification is shown in Table 3. The performance indices like ITAE and ITSE are reduced to certain extent.

Table 3. Comparison of performance characteristics

	Settling time (seconds)	Max. Overshoot (%)	ITAE	ITSE
MLS-ALPHA	0.000140	0.0202	0.5405	0.0006
MLS-BETA	0.000143	0.0207	0.5514	0.0006
MLS-DELTA	0.000144	0.0208	0.5556	0.0006
MLS-ZN	0.5030	37.6922	1.3769	0.0269

6. CONCLUSION

An optimized PID controller is designed to levitate the metal ball of the MLS. The simplified mathematical model has been developed and the transfer function of the MLS has been established. The parameters of the conventional PID controller are optimized by using a meta-heuristic algorithm known as GWO. The proposed optimization technique ensures the improvement of the time domain and as well as the frequency domain specifications by minimising the performance indices of the system. The performance index chosen in this paper are ITAE and ITSE. The eminent properties of optimization technique like exploration and exploitation are guarantees by the GWO algorithm. The effectiveness of the proposed techniques is validated by comparing the results with the classical design techniques.

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