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INTELLIGENT SELF-TUNING PID CONTROLLER USING HYBRID IMPROVED PARTICLE SWARM OPTIMIZATION FOR ULTRASONIC MOTOR

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ABSTRACT

Ultrasonic Motor (USM) is a new important actuator that has superior features than the common electromagnetic motor. But, due to no-accurate mathematical model and characteristic changes during operation, it is hard to control USM. In this paper, an Intelligent Self-tuning PID controller using Hybrid Improved Particle Swarm Optimization (HIPSO) for USM is presented. The proposed HIPSO is developed to improve PSO by using combination of three strategies, i.e., additional part for creating new sharing information, adaptive inertia weight for obtaining properly balance quickly and mutation operator for maintaining diversity within particles. Experimental results show that the proposed control scheme can greatly enhance the performance of USM servo system in term of convergence speed and position accuracy.

Keywords: *Ultrasonic motor (USM), PID controller, intelligent self-tuning, particle swarm optimization (PSO), swarm intelligence*

1. INTRODUCTION

Ultrasonic motor (USM) is a new type motor that is driven by ultrasonic vibration of piezoelectric parts. USM was developed since 1982 and has been widely used in many applications where the size, torque, and other requirements couldn't be satisfied by the common electromagnetic motor. USM has some excellent features, e.g., compactness, lightweight, high-torque, high-position accuracy, EMC compliance, self-brake without power, silence, and quick response [1], [2]. The common applications of USM are as actuator in auto-focus of camera, micro-robot, MRI (magnetic resonance imaging), and other medical equipment. In the future, USM will be an important actuator in many specific applications.

However, due to no-accurate mathematical model and characteristic changes during operation, the control of USM is not easy. Many control strategies have been proposed for USM. There are two approaches for control USM, i.e., model-based controller and model-free controller. Model-based controllers, e.g., robust controller and generalized predictive control, have been applied successfully for USM. However, it is difficult in achieving a best performance because they used simplified model of USM that has an enough large of modelling-error. Also, they require mathematical calculation that is not easy [3], [4]. Model-free controllers are easier for control USM because they can be designed without using any mathematical model of plant. Hence, many model-free controllers have been developed for USM, e.g., FLC [5], Fuzzy-PID [6], BPNN-PID [7], PSO-PID [8], SMC [9], MRAC [10], IMC-PID-NN [11], NN-PID [12]. Recently, the research to develop a proper control scheme for USM is still being conducted intensively.

In order to overcome difficulties in controlling USM, we proposed a new control strategy, called Intelligent Self-Tuning PID Controller using Hybrid Improved PSO (HIPSO). The proposed HIPSO is a new development of PSO to reduce its shortcoming by using combination of three strategies, i.e., additional part for creating new sharing information, adaptive inertia weight to obtain the balance quickly, and mutation operator to keep diversity within particles and inhibit premature convergence. The proposed method is to improve the previous research and increase the performance of USM. In the research, we investigated new control strategy and compared with the previous methods.

2. PARTICLE SWARM OPTIMIZATION

PSO is a population based stochastic optimization method using the concept of cooperation inspired by the behavior of organism, such as birds flocking, in search for food [13]. The outline for PSO is marked as follows. Let consider the optimization problem of maximizing the evaluation function $f: M \rightarrow M' \subset R$ for variable $x \in M \subset R^n$. Let there be N particles (mass point) on M dimensional space, where the position vector and velocity vector of $i(= 1,2,3,....,N)$ th particle for m searching number are x_i^m and v_i^m . The best position for each particle in the evaluation function $f(x)$ of $x_i^1, x_i^2, ... x_i^m$ searching point is represented as Pb_i (*Pbest*), while the best position of $f(x)$ in the searching point for the whole particle is represented as gb (*gbest*). The particles are manipulated according to the following recurrence equations:

$$v_i^{m+1} = w.v_i^m + c_1.r_1.\{Pb_i - x_i^m\} + c_2.r_2.\{gb - x_i^m\} \quad (1)$$

$$x_i^{m+1} = x_i^m + v_i^{m+1} \quad (2)$$

where w is the inertia weight; c_1 and c_2 are cognitive and social constant; r_1 and r_2 are random numbers. There are three parts or vectors that affect the particle's movement, i.e.: momentum vector ($w.v$), cognitive vector ($Pb - x$), and social vector ($gb - x$). According to Eq. (1) and Eq. (2), the particle's movement in PSO can be illustrated in Fig. 1. The next position of particle is the resultant of three vectors.

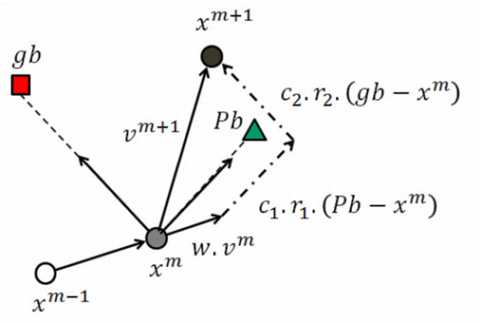

Fig. 1 Particle's movement in PSO

3. THE PROPOSED HIPSO

The standard type of PSO has shortcoming, namely premature convergence and easy to get stuck into local optima. It was reported that the causes of the shortcoming are: (1) unbalance between exploration-exploitation ability; (2) lost diversity and lack information due to fast rate flow in sharing information and particle's movement. The exploration ability or global search ability is an ability of PSO to globally search and identify a region with potentially high qualified solution. The exploitation ability or local search ability is an ability of PSO to refined search in order to get the best solution as accurate as possible in the region. Due to stronger exploitation, particles are less aggressive for searching a global best solution. Therefore, particles tend to be stagnant. Due to stronger exploration, particles are too aggressive and have difficulty in getting or stop in a global solution area.

The standard type of PSO was dominated by the social and cognitive behavior of swarm. Particles are greatly influenced by its previous best particles (Pb) and the global best particle (gb). The movement of particles is governed by three parts: (1) the inertial part $w.v^k$; (2) the cognitive part $Pb - x^k$; (3) the social part $gb - x^k$. With the movement of particles, particles will follow the global best particle and close to Pb and gb, and then $Pb - x^k$ and $gb - x^k$ becomes small. Once the gb fall into local optima, all the particles will quickly follow and converge to the local optima. The cognitive part and social part of each particle will be near to zero because $x^k = Pb = gb$. As a result, the velocity of each particle tends to zero, and the updating equation of position is invalid. Finally, all particles lost diversity and will be stagnated and hardly escape from local optima. Moreover, due to fast rate flow and 'one-way' mechanism in sharing information, particles move quickly toward the better area searching. However, during searching process they often lost information because the cognitive and social factors quickly become small. Due to the lack information, particles tend to prematurely converge.

To overcome those problems, we propose combination of three strategies at the same time. Firstly, we add a new part or factor or vector in particle's movement to compensate the lack information and fast rate flow in sharing information. The new factor connects between personal and global best position. The new factor together with the original factor, i.e., cognitive and social factor, will influence the current particle to determine the next position of particles, so that the ability to find the best solution can be increased. We called the new factor as the socio-cognitive factor. Secondly, we use adaptive inertia weigh to accelarete in achieving a proper balance between exploration-explotation ability [14]. Inertia weight is most important parameter to improve PSO. However, adjusting inertia weigh to achieve a proper balance is difficult. To overcome the difficulty in adjusting inertia weight, we insert feedback mechanism to take a fitness value of *pb* and *gb* and use these values to calculate inertia weight automatically. Due to feedback mechanism, an inertia weight can be adjusted easily adaptively according to the swarm condition. Thirdly, to more ensure that the trapped particles can escape from local optima and to avoid premature convergence, we propose the mutation operator. The main idea of the proposed method is taken from the advantage of mutation operator in GA to give more diversity of particles for jumping-out from local optima [15]. Mutation in GA is flipping a bit of chromosome. Mutation rate are typically quite low (0.1-1.0 % is a common range), so that at the beginning the effect of mutation is relatively small and increasing toward the end. Mutation in PSO is operated on stagnated particles by giving small random variation. We use mutation operator on global best position of particle with small random variation below 10%. Therefore the diversity of populations can be maintained and prevent premature convergence or fall in the local optima. Thus, the equations of the proposed method are changed as follows:

$$v_i^{m+1} = w \cdot v_i^m + c_1 \cdot r_1 \cdot \{Pb_i - x_i^m\}$$

$$+c_2 \cdot r_2 \cdot \{gb - x_i^m\} + c_3 \cdot r_3 \cdot \{gb - Pb_i\} \quad (3)$$

$$w = w_o - \left(\frac{gb^*}{Pb_i}\right) \quad (4)$$

$$gb^* = gb.\gamma \quad (5)$$

$$\gamma = 1 + 0.1 \cdot r \quad (6)$$

where gb^* is mutated gb, γ is mutation rate (in here, below 10%), r is random number, w_o is an initial value of inertia weight.

The new mechanism of information sharing in HIPSO can be illustrated in Fig. 2. Now, the next position of particle is the resultant of four vectors.

3. APPLICATION OF HIPSO FOR SELF-TUNING PID CONTROLLER

In this work, the PID controller is used as controller. It is comprised of three components: a proportional part, a derivative part and an integral part [16].

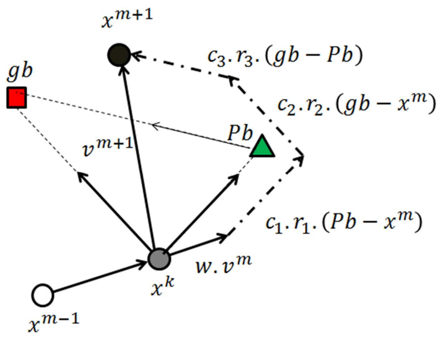

Fig. 2 New Particle's movement in HIPSO

The PID controller can be expressed in transfer function equation as follows:

$$C(s) = K_p + \frac{K_i}{s} + K_d.s \quad (7)$$

where the K_p is proportional constant, K_i is integral constant and K_d is derivative constant. The critical process in designing PID controller is tuning process or process to determine the gain of PID controller. The performance of system controlled by PID absolutely depends on this process. The tuning process will become more difficult for system with strong nonlinearity, complexity, uncertainty and disturbances.

To avoid these difficulties and to compensate the characteristic changes of USM during operation, the proposed HIPSO is used as intelligent self-tuning scheme. Due to this scheme, the gains of PID controller can be adjusted automatically according to the behavior of USM. The design of HIPSO-based PID controller is shown in Fig.3. Each particle of HIPSO is set to handle three gains of PID controller. The signal *e(k)* will be entered for HIPSO algorithm and subsequently evaluated in the fitness function to guide the particles during the optimization process. The fitness function for the proposed method is calculated based on ISE (integral square error) criterion as given as follows:

$$\text{fitness} = \frac{1}{1+\sum_0^T e(k)^2} \quad (8)$$

where *e(k)* is error signal sampled in every 1 [ms], *T* is discrete time-calculation. In here, we use 10 discrete-time calculation, so that every 10 [ms] the position and velocity of particles and the gain of PID controller are updated.

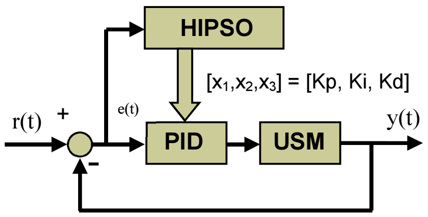

Fig. 3 HIPSO-based PID controller

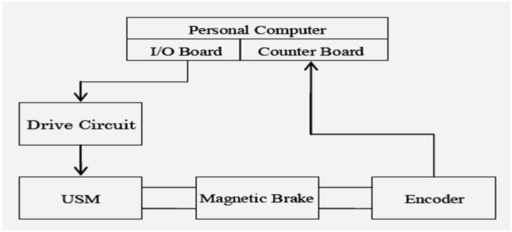

Fig. 4 USM servo system

The USM servo system constructed in this study is shown in Fig. 4. USM, the electromagnetic brake and the encoder are connected on a same axis. The position information from an encoder is transmitted to the counter board embedded into a Personal Computer (PC). Meanwhile, according to error resulted from the comparison between the output and reference signal, the control input signal which is calculated in PC is transmitted to the driving circuit through the I/O board and oscillator. In each experiment, the load is added or not is discussed to observe the changes of the USM's characteristics. While the voltage of 12 [V] is imported, the force of 0.25 [N.m] could be loaded to the shaft of the USM. The specifications of USM servo system is shown in Table 1.

Table 1: The Specifications Of USM Servo System

USM	Rated rotational speed : 100 [rpm]
	Rated torque : 0.5 [N.m]
	Holding torque : 1.0 [N.m]
Encoder	Resolution : 0.0011 [deg]
Load	0 to 0.5 [N.m]

4. EXPERIMENT RESULT

Some experimental results are provided in this Section to verify the effectiveness of the proposed HIPSO-based PID controller for USM. We also have compared our method with previous methods, i.e., fixed-gain PID, PSO-LDW based PID, PSO-NDW based PID, PSO-RIW based PID, APSO based PID and APSO-RIW with the same system condition.

The reference input *r(t)* is a rectangular signal. The amplitude is set from +45 [deg] or clockwise (CW) rotation to -45 [deg] or counter clockwise (CCW) rotation. The period is 4 [sec]. Two test conditions are provided in the experimentation, which are the unloaded condition and the loaded condition. The loaded condition is the addition of load from electronic brake with 0.25 [N.m]. Each method has been performed for 10 trials of CW and 10 trials of CCW. The parameters of PSO and modified PSO are set as follows: particle number, $n = 5$; cognitive constant, $c_1 = 1.0$; social constant, $c_2 = 1.0$; socio-cognitive constant, $c_3 = 1.0$; $w_{max} = 0.8$; $w_{min} = 0.3$; $w_o = 1.4$.

Firstly, the conventional fixed-gain PID must be tuned by or hand-tuned method [17]. We found that the gains of PID controller are $K_p = 0.3692$; $K_i = 12.175$; and $K_d = 0.000085$. The position accuracy in histogram of USM servo system controlled by the fixed-gain PID, PSO-LDW (the standard type of PSO) based PID, and proposed HIPSO-based PID controller are shown in Figures 5-10, respectively. Each bucket of the histogram is set to a width of 0.0011 [deg]. It is a resolution of the encoder. In Figure 5 and 6, it seems a high density around the zero for the unloaded condition and be distributed uniformly (away from the zero) for the loaded condition. We can say that the conventional fixed-gain PID controller shows enough good accuracy in the unloaded condition, but becomes poor and inaccurate in the loaded condition. The determined gains are only suitable for the unloaded condition. If the plant's behavior is changed (i.e., due to the loading), it is necessary to re-tune PID and it is drawback of the fixed-gain PID. The conventional fixed-gain PID cannot compensate the characteristics changes of USM during operation.

The position accuracy of USM can be improved by using PSO-LDW based PID and better when by using the proposed HIPSO based PID controller as shown in Figures 7-10, respectively. The proposed method shows a high density around the zero both the unloaded and the loaded conditions. It means that the HIPSO algorithm can solve the optimization problem in tuning the PID controller with better results than previous methods. The proposed HIPSO algorithm can improve the performance the standard type of PSO. It can be seen clearly that self-tuning PID controller can compensate the characteristic changes of USM due to the loading effect. The gains PID are automatically adjusted according to the plant's behavior. There are characteristic differences between the CW and the CCW rotation. The position accuracy of the CW rotation is better than the CCW rotation. It may be caused by the use of one vibration source to generate the travelling wave in the stator of USM and difference between CW model and CCW model.

The statistical analysis of all methods in term of the average of error (*Ave_Ess*) and the frequency of zero-error (*Zero_Ess*) in 20 trials is listed in Table 2. The meaning of zero-error is the error whose value is smaller than the resolution of encoder (i.e., 0.0011 [deg]). It is also called as success-rate (*SR*). From Table 2, it's easy to see that the proposed HIPSO based PID controller shows better performance in all parameters than the previous methods in both conditions. The position accuracy of the proposed HIPSO presents an average of 0 [deg], and a zero-error of 20 trilas or *SR* of 100% in both conditions. According to those results, the proposed HIPSO algorithm may guarantee a good sense of accuracy and can increase the probability in obtaining a best solution. Compared with the common PSO-LDW based PID controller, the proposed HIPSO based PID controller can increase performance significantly in both the unloaded and loaded condition.

The fitness convergence characteristic of PSO-LDW and HIPSO is shown in Figure 11. It seen clearly that the particles HIPSO achieve faster convergence than the previous methods. The particles of HIPSO achieved convergence in 0.18 seconds, while PSO-LDW achieved convergence in 0.27 seconds.

Table 2 Comparison Of The Average Steady-State Error

Methods	Ave Ess		Frequency of Zero Ess in 20 runs	
	No-load	Load	No-load	Load
PID	5.78×10^{-4}	3.31×10^{-3}	14	5
PSO-LDW	5.11×10^{-4}	8.94×10^{-4}	14	12
PSO-NDW	4.17×10^{-4}	4.44×10^{-4}	15	13
PSO-RIW	1.83×10^{-4}	3.31×10^{-4}	17	15
APSO	1.67×10^{-4}	2.44×10^{-4}	18	18
APSO-RIW	0	6.10×10^{-5}	20	19
HIPSO	0	0	20	20

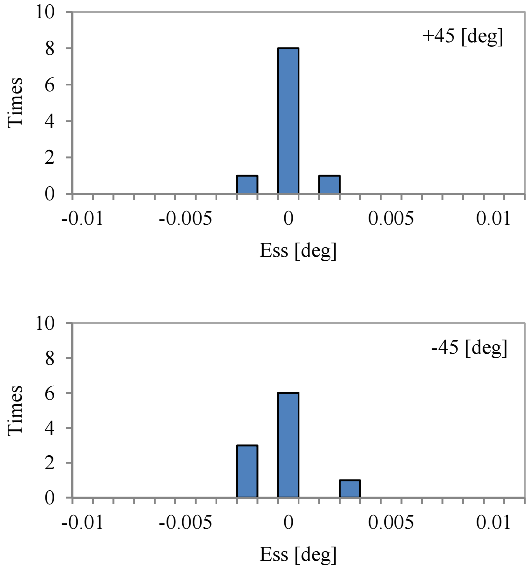

Fig. 5 Accuracy of USM using PID controller (unloaded)

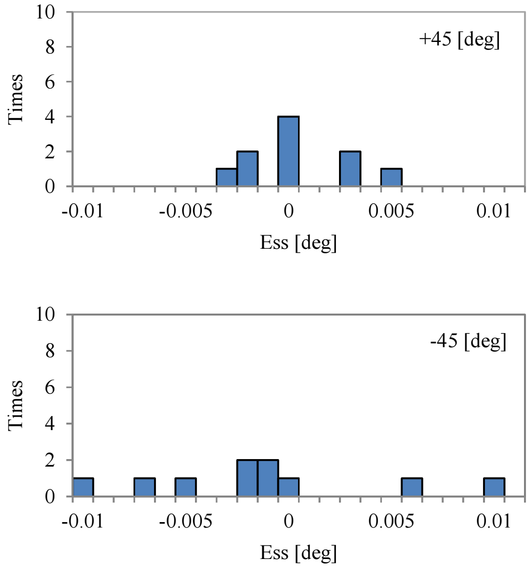

Fig. 6 Accuracy of USM using PID controller (loaded)

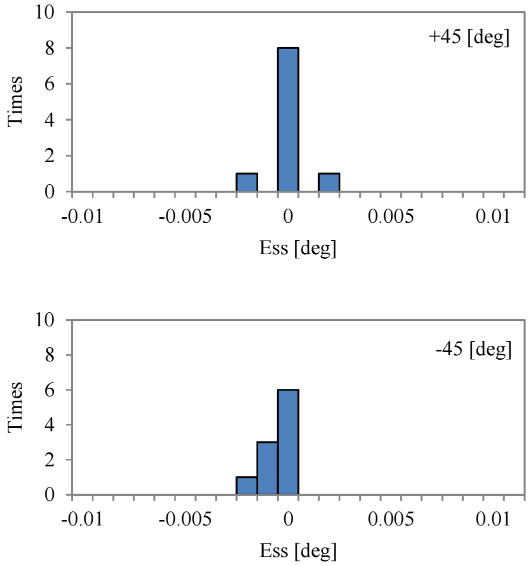

Fig. 7 Accuracy of USM using PSO-LDW PID controller (unloaded)

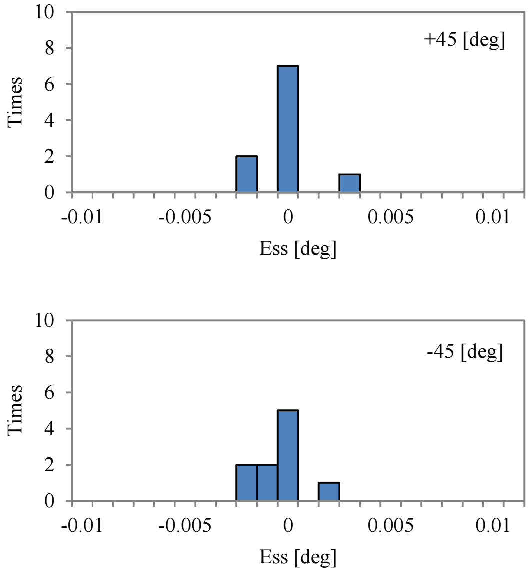

Fig. 8 Accuracy of USM using PSO-LDW PID controller (loaded)

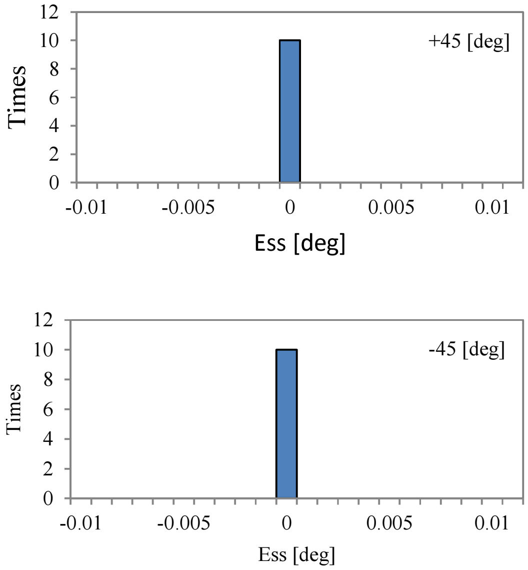

Fig. 9 Accuracy of USM using HIPSO-PID controller (unloaded)

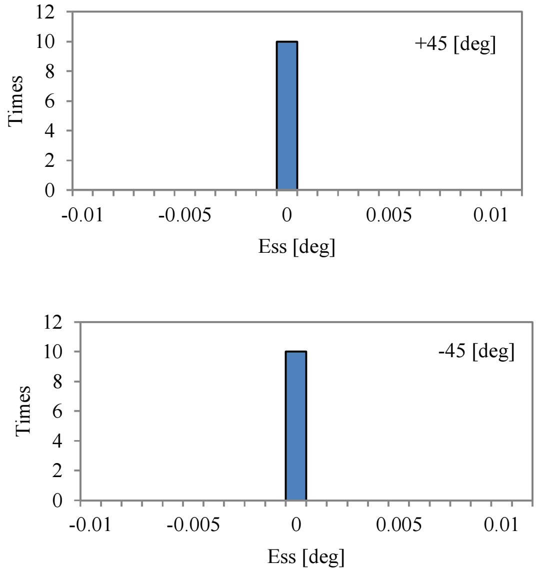

Fig. 10 Accuracy of USM using HIPSO-PID controller (loaded)

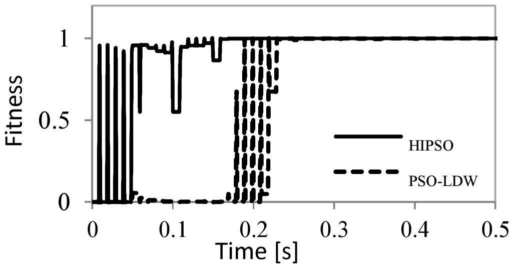

Fig. 11 Covergence speed

5. CONCLUSION

In this paper, the performances of HIPSO-based PID controller on USM have been investigated and extensively. The results are compared with the fixed-gain PID and other modified PSO-based PID controller by real application of the USM servo system. We could conclude that the proposed HIPSO would have the superiority to previous methods in term of convergence speed and position accuracy of USM. Combination of three strategies has proved efectively for reducing the risk of premature convergence and fall into local optima.

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