Variable Gain PID Control of Ultrasonic Motor Using a Novel Hybrid PSO with Improved Searching Ability

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Abstract

The Ultrasonic Motor (USM) is a new type motor that get driven by frictional force. At present, since USM has excellent features, it is used in various fields such as in autofocus of cameras, actuators of devices in MRI environment, and micro robots. However, because the dynamic characteristics of USM vary according to different temperature, humidity, and load conditions, mathematical modeling of USM is difficult. Thus, PID control has been used for control of USM conventionally. However, conventional PID control with fixed gains cannot compensate the non-linear characteristic variation of USM. In this research, we propose a Novel Hybrid PSO (NH-PSO) for USM control. This proposed method applies Particle Swarm Optimization (PSO) method to tune the optimized PID gains automatically. The optimized gains in USM control can be obtained in real time by using the proposed method. The control of USM with high accuracy can be achieved by applying the proposed method compensating the characteristics.

Keywords: ultrasonic motor, PID control, variable gain, particle swarm optimization, inertia weight approach, nonlinearly decreased inertia weight PSO, random inertia weight PSO, real-time control.

1. Introduction

The Ultrasonic Motor (USM) is a new type of motor which is driven by frictional force. Different from conventional electronic motors, the main components of USM are a rotor and a stator. When high frequency

alternating voltage is added to the piezoelectric element on the stator of USM, mechanical vibration will be generated in the stator. The frictional force between the rotor and the stator, which is caused by the ultrasonic wave generated from the vibration, will drive the rotor to move in certain direction. USM has excellent features, such as Electro Magnetic Compatibility (EMC) compliance, high torque, silence operation, compact size, lightweight, quick response, and low speed run with no gear required. Thus, USM is used in various fields such as in autofocus of cameras, actuators of devices in MRI environment, and micro robots⁽¹⁻⁴⁾. Since USM is driven by frictional force, dynamic characteristics vary according to different conditions. For this reason, there are difficulties in mathematical modeling based on physical analysis⁽⁵⁾. Thus, PID control has been used for control of USM in previous research. However, PID control with fixed gains cannot compensate the non-linear characteristics of USM, which is caused by a temperature or humidity change or a load change in USM driving. Thus, the performance of the control of USM degrades owing to the characteristic variations. Thereby, the optimization of three PID gains of K_p , K_I , and K_D is necessary⁽⁶⁻¹¹⁾.

Therefore, in this research, we use Particle Swarm Optimization (PSO) as a method to tune the PID gains for obtaining high control performance in USM control⁽¹²⁾. With the application of PSO, there are no requirements about USM modeling or differential information in optimization. Moreover, since PSO is effective in non-linear optimization, we apply it in the proposed method corresponding to the non-linear change of characteristics. The effectiveness of the proposed method is verified based on experiments.

2. Particle Swarm Optimization

PSO was introduced by Dr. Eberhart and Dr. Kennedy in 1995 through simulations of the simplified social model⁽¹³⁾. It is a new population-based probability-like optimization algorithm inspired by social behavior. It is an algorithm which employs the social action of swarm (e.g. bird, fish, and insect) to find the optimized solution in searching space. The basic concept of PSO can be explained as the follows. In the swarm, each particle contains the information of velocity and position searches the optimal solution in searching space. The information is shared in the swarm between the particles. Based on this information shared in the swarm, the position and velocity of particles can be updated with convergence to optimal solution. Since solutions are evaluated by a designed fitness function, there is no requirement of continuity or differential information by using PSO. In addition, PSO is considered as an algorithm which is simpler than Genetic Algorithm (GA). It is effective in non-linear optimization problems. The constitution principle of PSO is explained in the following. The particles in multidimensional space have a position vector and a velocity vector. The particle memorizes the best position of its own. The particle which is at the local best position impart positional information to the particle swarm of neighborhood. The evaluation of the best position uses the evaluation function. Therefore, the information of the best position of all particles is imparted to the whole particle.

Here, we think about the issue of optimization to maximize the evaluation function $f: M \rightarrow M' \subset R$ with respect to the variable $x \in M \subset R^n$. The particle of N

exists in spatial M . At time of repetition number of times $m(= 0,1,2, \dots)$ and the $j(= 0,1,2, \dots, N)$ -th particle, the position vector and the velocity vector become x_j^m and v_j^m . $Pbest$ is the point that the evaluation function $f(x)$ becomes maximum in search point $x_j^1, x_j^2, \dots, x_j^m$ of each particle of PSO. In addition, $Gbest$ is the point that $f(x)$ becomes maximum in search point of the whole particle. Also, $Pbest$ shows the best position that individual particles discovered so far. In addition, $Gbest$ shows the best position that the whole swarm discovered so far. From this information, PSO updates position vector x_j^m and velocity vector v_j^m of individual particles.

The update of position and velocity of each particle is repeated using the following recurrence formulae.

$$v_j^{m+1} = \omega \cdot v_j^m + c_1 \cdot r_1 \cdot (Pbest_j - x_j^m) + c_2 \cdot r_2 \cdot (Gbest - x_j^m) \quad (1)$$

$$x_j^{m+1} = x_j^m + v_j^{m+1} \quad (2)$$

Where ω represents the inertia weight; r_1 and r_2 are random numbers drawn from a uniform distribution of interval $[0,1]$. These are generated in each component. c_1 and c_2 are positive constants, called cognitive and social scaling parameters respectively (usually, $c_1 = c_2$). c_1 and c_2 show the weight coefficient with respect to the search of the best position of each particle and whole particle swarm. The particle's movement in PSO algorithm using Eq.(1) and Eq.(2) can be illustrated in Fig.1. The movement of particles is governed by three parts: (1) the inertial part, $\omega \cdot v_j^m$; (2) the cognitive part, $(Pbest_j - x_j^m)$; (3) the social part, $(Gbest - x_j^m)$. The velocity vector of v_j^{m+1} is formed based on three vectors as shown in Eq.(1).

Fig. 1. Movement of particle in PSO.

In this research, we think about solution space $M_{PID} \subset R^3$ of K_p axis, K_i axis, and K_d axis of the PID gain in the PID control. This solution space M_{PID} is three-dimensional coordinate space. Each particle of PSO expresses it as a point in solution space M_{PID} . Therefore, we apply optimization by PSO using this.

3. Novel Hybrid PSO

The inertia weight ω is an important parameter to decide balance between the local area search ability and the wide area search ability on the particle of PSO. Generally, if a value of the inertia weight is big, the particle performs the wide area search of the solution space. In addition, if a value of the inertia weight is small, the particle performs the local area search of the solution space. Accordingly, the technique to change inertia weight and to coordinate search ability of PSO is called Inertia Weight Approach (IWA)^(14,15). Linearly Decreased Inertia Weight PSO (LDW-PSO) which a linear decrease function is given in ω and Nonlinearly Decreased Inertia Weight PSO (NDW-PSO)⁽¹⁶⁾ which a non-linear decrease function is given in ω is used for conventional IWA. These algorithms decrease ω based on function. The function decreases to minimum ω_{min} which we set optionally from maximum ω_{max} which we set optionally. Thus, the particle performs the wide area search at early stage of search and performs the local area search at final stage of search. Especially, NDW-PSO can change the ratio of the wide area search and the local area search using function. Thus, PSO balances the local area search with the wide area search. However, there is a problem in this algorithm. It is that the local area search decreases at early stage of search. On the other hand, it is that the wide area search decreases at final stage of search. Consequently, the particle may fall into a local solution. Particularly, this tendency is high in the dynamic environment.

Therefore, in this research, we suggest Novel Hybrid PSO (NH-PSO) that improved searching ability. NH-PSO combine advantage of NDW-PSO and Random Inertia Weight PSO (RIW-PSO). RIW-PSO in particular is superior in ability for search. The proposed algorithm compares the evaluation value $Fitness_{j-1}^m$ of the previous particle with the evaluation value $Fitness_j^m$ of the current particle in NDW-PSO. If the evaluation value $Fitness_j^m$ of the current particle decreases, RIW-PSO is applied to particle x_j^{m+1} of the same particle number in next repetition $m+1$. Therefore, this algorithm can compensate a load change in final stage of search. As a result, local optimization problem

can be compensated.

$Fitness_j^m$ is derived using the following Eq.(3).

$$Fitness_j^m = \frac{1}{1 + \sum_{k=0}^T \{e(k)\}^2} \quad (3)$$

Where T is the expected calculation-time. In experiment, we used $T = 10$ ms.

The proposed algorithm compares the evaluation value $Fitness_{j-1}^m$ of the previous particle with the evaluation value $Fitness_j^m$ of the current particle using Eq.(3). When $Fitness_{j-1}^m \leq Fitness_j^m$, Eq.(4) can be used. When $Fitness_{j-1}^m > Fitness_j^m$, Eq.(5) is employed. By this way, the parameter ω is decided in the proposed algorithm.

$$\begin{cases} \omega = (\omega_{max} - \omega_{min}) \cdot \left(\frac{m_{max} - m}{m_{max}} \right)^\tau + \omega_{min} & (Fitness_{j-1}^m \leq Fitness_j^m) \end{cases} \quad (4)$$

$$\begin{cases} \omega = (\omega_{max} - \omega_{min}) \cdot r + \omega_{min} & (Fitness_{j-1}^m > Fitness_j^m) \end{cases} \quad (5)$$

r in Eq.(5) is random numbers drawn from a uniform distribution of interval $[0,1]$; τ in Eq.(4) is parameter called nonlinear index number. The value of nonlinear index number will determine the degree of nonlinear path of decreasing inertia weight ω . The local search ability will be increased if the value of the nonlinear index is large. Meanwhile, the global search ability will be decreased. The influence of nonlinear index number is shown in Fig.2.

In the application of the proposed method, when the most suitable gains change according to the characteristic variation, the searching method will switch to RIW-PSO with better searching ability. By this way, this NH-PSO follows the appropriate most suitable solution. We can optimize a particle efficiently using NH-PSO.

Fig. 2. The impact of nonlinear index number.

PID controller using NH-PSO is shown in Fig.3. K_p , K_I , and K_D of each PID gain are optimized using NH-PSO algorithm like Fig.3.

4. Actual Machine Experiments

4.1 Experimental Conditions

We performed the actual machine experiment to confirm usefulness of NH-PSO in this research. The constitution of USM servo system of experimental equipment is described in the following. USM, the electromagnetic brake, and the encoder are connected on a same axis. First, the angle positional information from an encoder is sent to Personal Computer (PC) through counter board. Second, in PC, an error signal is calculated based on the difference between target value and the angle positional information of encoder. Third, a control signal is calculated based on this error signal and sent to driver circuit through IO board. Finally, USM works as intended.

The target setting is the following square wave. The period is 4 sec. The amplitude is 45 deg. This movement period is 10 cycle. Each initial gains of the PID controller are $K_p = 1.3$, $K_I = 70$, and $K_D = 0.0001$. The parameters of PSO are set as follows: (1) the particle number, $N = 5$; (2) the cognitive constant, $c_1 = 1.0$; (3) the social constant, $c_2 = 1.0$; (4) the maximum value of inertia weight, $\omega_{max} = 0.9$; (5) the minimum value of inertia weight, $\omega_{min} = 0.4$; (6) the nonlinear index number, $\tau = 1.5$. The specifications of USM servo system is shown in Table 1.

Fig. 3. NH-PSO PID controller.

4.2 Experimental Results

By the experiment, the steady-state error was measured 20 times. Fig.4 and Fig.5 show this result by histogram. Fig.4 and Fig.5 show the position accuracy of USM in unloaded and loaded conditions. The transverse of graph indicates the size of the error. The value of the steady-state error measured an error in front of 10 ms where the sign of the target input signal is switched. In unloaded condition and loaded condition, we were able to confirm that the error of NH-PSO of the proposed method decreased more than NDW-PSO of the traditional technique.

Table 1. Specifications of USM, encoder and load.

USM	Rated rotation speed: 100 rpm
	Rated torque: 0.5 Nm
	Holding torque: 1.0 Nm
Encoder	Resolution: 0.0011 deg

(a) NDW-PSO.

(b) NH-PSO.

Fig. 4. Position accuracy of USM (unloaded).

(a) NDW-PSO.

(b) NH-PSO.

Fig. 5. Position accuracy of USM (loaded).

In consequence, NH-PSO of the proposed method compensated the non-linear change of motion properties of USM. In addition, we confirmed that the control performance of the proposed method was better than the results of the traditional method.

5. Conclusions

In this research, we propose NH-PSO with improved searching ability as control technique to compensate nonlinearity in USM control. In experiments, we compared the results of the propose method NH-PSO with the results of the method NDW-PSO proposed in previous research. The effectiveness of the proposed method has been confirmed. The USM control with high accuracy can be achieved by applying the proposed method.

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