Hittite Journal of Science and Engineering, 2015, 2 (2) 159-164
ISSN NUMBER: 2149-2123
DOI: 10.17350/HJSE19030000020

AC Servo Motor Speed and Position Control Using Particle Swarm Optimization (PSO)

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ABSTRACT

In this article, a new design method, called Particle Swarm Optimization (PSO), is used for the determination of PID control parameters; this is designated for the controlling of the speed and the position of the AC servomotor. For the determination of the decision parameters AC servomotors are mathematically modelled. Rise time, settling time, and overshoot are taken into consideration, during the optimization process. Controller's performance is determined based on different criteria, such as, ITAE (Integral of Time Weighted Absolute Error), IAE (Integral of Absolute Error), ISE (Integral of Squared Error) and ITSE (Integral of Time Weighted Squared Error). Superiority and accuracy of the proposed technique was verified by simulation results. In addition, considering the quality of the obtained results, proposed technique is found effective and strong in reduction of the error of motion control systems.

Article History:
Received: 2015/09/30
Accepted: 2015/12/11
Online: 2015/12/30

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Key Words:
Particle Swarm Optimization; PSO, Servomotors; Motion Control.

INTRODUCTION

Without specific design and application difficulties, servomotors, which are regarded as sequenced systems, are preferred in non-linear and dynamic working conditions [1-10]. AC servomotors are also widely used in various control applications such as: numerical control, precise robot applications, and CNC machinery [11-14]. Along with its electrical and mechanical dynamics, one of the most important reasons these motors are so popular is their high efficiency. Ac servomotors need an accurate feedback response for the reference position. The feedback signals are important for servomotor to quickly respond to on-off operations and to maintain its steady state in sudden load changes. In automation applications, where feedback signals are used, such as speed, position and torque, even if a mathematical model is correctly constructed, using this mathematical model may cause complex problems and higher costs. Therefore, implementation of some control algorithms to uncertain, inaccurate, not well defined time-variable and complex systems may be impossible. Some of the leading problems of the complex systems are as follows: non-linearity of system, unknown mathematical model, difficulties in measurement, substantial time-variability of model parameters etc. Therefore, instead of mathematical statements, intelligent techniques are needed.

Nowadays several methods can be used to solve complex computational problems inspired by nature. One of these methods is the particle swarm optimization (PSO) technique [15-21]. PSO, which is a population-based stochastic optimization technique and is developed by Kennedy and Eberhart in 1995, is inspired by bird flocks' social behaviors.

In the algorithm, particles are defined as points in an N dimensional space, where each dimension represents a decision variable. Every particle determines its flying direction based on both its and the swarm's directions. Namely, unlike the evolution based techniques, particles benefit from their and the swarm's previous experience in reaching to the solution.

The main aim of the research was to specify optimal K_p, K_i and K_d (PID) parameters, which are needed for a better movement control; and particle swarm optimization (PSO) was used to determine the optimum PID parameters.

MATERIAL AND METHODE

Servo Control Unit

Control signal applied to the servomotor is limited by the signal voltage, which is generated by the modulator. In addition, the control voltage for the formation of the magnetic rotary field, the reference voltage must be the same frequency.

Technical specifications of the servomotor of the control system are given in Table 1.

Table 1. AC Servomotor parameters.

Model		*K40030H*
Rated Power		*400W*
Rated Torque		*1.3 Nm*
Rated Speed		*3000 r/min*
Maximum Rotation Speed		*6000 r/min*
Maximum Torque		*3.8 Nm*
Rated Current		*2.4 A(rms)*
Maximum Current		*10.2 (0-p)*
Rotor Inertia	*Without Brake*	0.26×10^{-4} *kgm*^{2}
	With Brake	0.28×10^{-4} *kgm*^{2}
Mechanical Time Constant	*Without Brake*	*0.43 ms*
	With Brake	*0.46 ms*
Electrical time constant		*3.4 ms*

Particle Swarm Optimization (PSOa)

PSO algorithm starts with a population of random solutions and updates the population in each iteration until it reaches optimum solution. Every particle in a population represents a solution and it produces an answer for every unknown. These answers show a particle's position in the solution space. Every particle kept the memory of its best solution until the current iteration. This solution is called p_{best}. G_{best} and is the best solution ever reached during the search of solution. In other words, g_{best} is the best of the p_{best}s. The g_{best} in the final iteration is the best solution reached by the swarm.

Velocities (V) and positions (X) of M particles in an N dimensional search space is represented as follows:

$$X = \begin{pmatrix} X_{11} & X_{12} & \dots & X_{1N} \\ X_{21} & X_{11} & \dots & X_{2N} \\ \dots & \dots & \dots & \dots \\ X_{M1} & X_{M2} & \dots & X_{MN} \end{pmatrix} V = \begin{pmatrix} V_{11} & V_{12} & \dots & V_{1N} \\ V_{21} & V_{11} & \dots & V_{2N} \\ \dots & \dots & \dots & \dots \\ V_{M1} & V_{M2} & \dots & V_{MN} \end{pmatrix} \quad (1)$$

In the above given matrix ith particle is denoted as:

$$X_i = \left[X_{i1} \quad X_{i2} \quad \dots \quad X_{iN} \right] \quad (2)$$

Particles' best positions (p_{best}) are represented as follows:

$$Pbest = \begin{pmatrix} Pbest_{11} & Pbest_{12} & \dots & Pbest_{1N} \\ Pbest_{21} & Pbest_{22} & \dots & Pbest_{2N} \\ \dots & \dots & \dots & \dots \\ Pbest_{M1} & Pbest_{M2} & \dots & Pbest_{MN} \end{pmatrix} \quad (3)$$

Every row in this matrix is an individual particle's best position in an N dimensional search space. Global best solution (g_{best}) is the best position among p_{best}s and given as a vector.

$$Gbest = \left[gbest_1 \quad gbest_2 \quad \dots \quad gbest_N \right] \quad (4)$$

Conceptually, PSO is based on the determination of particles' velocities in a given iteration considering their previous best positions and the swarm's best position. During the search process a particle's velocity and position are updated by using the following equations [15].

$$v_{i,d}^{(t+1)} = wv_{i,d}^{(t)} + c_1 r_1 (pbest_{i,d} - x_{i,d}^{(t)}) + c_2 r_2 (gbest_d - x_{i,d}^{(t)}) \quad (5)$$

$$x_{i,d}^{(t+1)} = x_{i,d}^{(t)} + v_{i,d}^{(t+1)} \quad (6)$$

$$i = 1, 2, \dots, m \; ; \quad d = 1, 2, \dots, \mathrm{n} \quad (7)$$

Social effect coefficients, c_1 and c_2 are positive numerals and they reflect the effects of the p_{best} and the g_{best} on a particle, respectively. Values of these coefficients are generally between 0.2 and 2. R_1 and r_2 are random coefficients and they provide stochastic to the technique. R_1 and r_2 values are randomly drawn between 0 and 1 [22-25]. W is the inertia coefficient and is selected mostly between 0 and 1. Inertia is used in order to balance global and local search capabilities. While higher inertia coefficients are good for global searches, a lower inertia coefficient increases local searches. Thus, the inertia balance the weights of global and local searches and aims at reaching the best solution with the minimum possible number of iterations. Particles benefit not only from the experience of the best particle but also the experiences of all other particles. W is linearly reduced throughout the PSO iterations by using the equation [15].

$$w = w_{maks.} - iter \frac{w_{maks.} - w_{\min.}}{iter_{maks.}} \quad (8)$$

Where *iter* is iteration number.

In PSO, particles change their positions until the maximum number of iterations is reached. The changes in the positions of the particles is given in Figure 1.

Where;

X^k : current position

X^{k+1} : position in the following iteration

V^k : current velocity

V^{k+1} : velocity in the following iteration

V^{Pbest} : p_{best} based velocity

V^{Gbest} : g_{best} based velocity

The algorithm, which is developed for movement control, is given in Figure 2. In this algorithm, initial positions and velocities of particles are randomly determined. Iteratively, new positions and speeds of particles are found and compared to their previous best positions. If the new position of a given particle is better than the previous best position of the particle, then the new position is recorded as the best position. But, if the new position is worse than the best position, the best position data is not updated. In addition, the best position of every particle is checked, and if the best of the best particle positions is better than the global best, then the global best is updated. These steps are repeated until the termination condition is met. The global best value reached at the last iteration of the algorithm is the best position reached by the algorithm.

Control Design

For the optimization of PID parameters of a movement control system PSO algorithm is used. Firstly, AC servomotor of the movement control system is mathematically modeled. Then, PID based control is applied to the system. According to this, general statement of PID controls as follows:

$$U(t) = K_p e(t) + \frac{1}{T_i}\int e(t)dt + T_d \frac{de(t)}{dt} \tag{9}$$

Where K_p, T_i, T_d, e(t) are proportional gain, integral time, derivative time and error between the input value and the output, respectively.

PSO-PID controller is shown in Fig. 3. Here, plant represents the system to be controlled, namely the transfer function. Transfer function is obtained by using Omron K40030H servomotor's specifications.

$$U(s) = K_p + \frac{K_i}{s} + K_d s \tag{10}$$

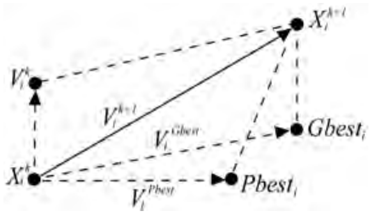

Figure 1. Illustration of PSO parameters as vectors.

Figure 2. PSO flow diagram for motion control.

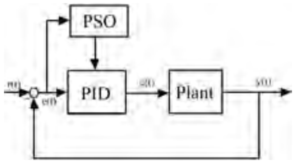

Figure 3. PSO-PID Controller.

PSO is used as an algorithm that will provide K_p, K_i and K_d values using the optimal output, thus creating the desired values.

Fitness Function

There are many methods in the literature for the determination of the performance of the controller. Some of these criteria are integral of absolute error (IAE), integral of time weighted absolute error (ITAE), integral of squared error (ISE) and integral of time weighted squared error (ITSE). These performance criteria have their disadvantages as well as their advantages. For example, one of the disadvantages of IAE and ISE are the solutions obtained by using them have longer settling time because, ISE performance criterion is totally independent of the time of the errors. Although ITSE performance criterion overcomes this disadvantage of ISE, derivative of its analytical expression is time-consuming.

Mathematical expressions of IAE, ISE, ITAE and ITSE criteria are as follows:

$$IAE = \int_0^\infty |r(t) - y(t)| dt = \int_0^\infty |e(t)| dt \tag{11}$$

$$ISE = \int_0^\infty e^2(t) dt \tag{12}$$

$$ITAE = \int_0^\infty t |e(t)| dt \tag{13}$$

$$ITSE = \int_0^\infty t e^2(t) dt \tag{14}$$

Ziegler-Nichols Method

One of the methods of PID parameter (K_p, K_i, K_d) tuning is Ziegler-Nichols method. This method is used in two ways:

1. Referring to open system response and PID parameters are determined like Table 2.

T, K and L signal wave period, system response slope and dead time, respectively.

Table 2. Ziegler-Nichols open loop adjustment parameters

Controller	K_p	$T_i=K_p/K_i$	$T_d=K_d/K_p$
P	T/L	-	0
PI	0.9 (T/L)	L/0.3	0
PID	1.2 (T/L)	2L	0.5L

2. Initially, according to the closed loop response given in Figure 4. K_i and K_d values are assumed to be 0. K_p value is increased until system starts oscillating. K_p value at this moment is named as K_u and the parameters are calculated as given in Table 3.

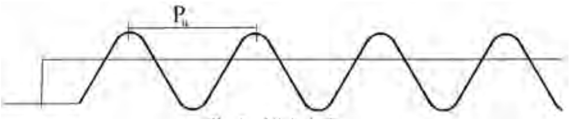

Figure 4. Closed loop system response of Ziegler –Nichols method.

Numerical Examples and Results

Transfer function for AC servomotor is obtained as given below:

$$\frac{Q_{(s)}}{E_{c(s)}} = \frac{K_1}{J_m s^2 + (B_m + K_2)s} \tag{15}$$

Table 3. Ziegler-Nichols Closed loop adjustment parameters

Controller	K_p	T_i	T_d
P	$K_u/2$	-	0
PI	K_u 2.2	$P_u/1.2$	0
PID	$K_u/1.7$	$P_u/2$	$P_u/8$

Table 4. K_p, K_i and K_d values obtained by using different criteria.

Tuning Method	K_p	K_i	K_d
Z-N PID	2.9400	0.0327	0.0081
PSO-PID1 (IAE)	4.9986	0.3359	0.9881
PSO-PID2 (ITAE)	4.8988	0.3966	0.9979
PSO-PID3 (ISE)	4.9352	0.8713	0.9932
PSO-PID4 (ITSE)	4.9975	0.0879	0.9992

Table 5. Settling time, rise time, overshoot obtained by using different criteria.

Tuning Method	Over-shoot (%)	Rise Time (s)	Settling Time (s)	SSE
Z-N PID	15.4	0.02040	0.09700	-
PSO-PID1 (IAE)	-	0.00128	0.06520	-
PSO-PID2 (ITAE)	$2.62x10^{-9}$	0.00080	0.00098	-
PSO-PID3 (ISE)	-	0.00127	0.06530	-
PSO-PID4 (ITSE)	-	0.00126	0.06410	-

In the above given transfer function some parameters are:

Transfer function above;

$$K_1 = 0.54167\,(Nm)/\mathrm{A}$$

$$J_m = 0.26 * 10^{-4}\, kgm^2 \,(\text{no brake})$$

$$B_m = 4.13802852 * 10^{-3}\,(\mathrm{Nm})/(\mathrm{rad/s})$$

$$K_2 = 0.012273318\, Nm/(rad/s)$$

Following PSO parameters are used and results are obtained under various performance criteria (IAE, ITAE, ISE, ITSE).

Population size = 100
$w_{maks.}$ = 0.9
$w_{min.}$ = 0.4
C_1 = 2
C_2 = 2
K_p = [0-5]
K_i = [0-1]
K_d = [0-1]

K_p, K_i and K_d values obtained by five different criteria are given in Table 4. Settling time, rise time, overshoot are shown in Table 5.

CONCLUSIONS

In this study, in order to determine the optimal K_p, K_i and K_d parameters (which are needed for a better movement control) PSO was used. Ziegler-Nichols, IAE, ISE, ITAE and ITSE were used as evaluation criteria within the algorithm. The difference between reference value and the system response was tried to be minimized. Different optimal PID values were compared to each other. Maximum overshoot value, rise time, settling time and steady-state error values have shown that different evaluation criteria caused the algorithm to respond differently for each of the five criteria. Among five criteria, the most acceptable values (minimum overshoot, the best rise time, and the best settling time) were obtained by using ITAE in a shorter time and without causing steady state error. With this study, it could be inferred that ITAE criterion within PSO is more appropriate for using in movement control applications.

In this research, PID parameters are determined using particle swarm optimization. This algorithm can apply not only in motor applications, but also other fields. In the future works comparison of PSO and other artificial intelligence (AI) techniques are planned in any subject such as optimum adhesive thickness for maximum strength. For this reason, the study can constitute the fundamentals of future works.

ACKNOWLEDGMENTS

We are grateful to Hitit University Scientific Research Projects Unit for supporting this project numbered (MUH01.12.004).

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