Optimization of Controller Structure Using Evolutionary Algorithm

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Abstract. PID-based controller structures are typically used in industrial control systems. However, in different areas the controller structures are slightly different. The differences are due to the modifications introduced by the expert. Expert, based on his experience and on trial-and-error method, adjusts the initial controller structure in order to obtain a better quality of control. In this paper a method based on an evolutionary algorithm is proposed. Usage of the proposed method makes this difficult and time consuming task easier and faster.

1 Introduction

In the literature there are presented various approaches to design of control system. Typically the following approaches are considered: controllers based on the combination of linear correction terms [37], e.g. PID controllers [29] (optionally with gain scheduling algorithm, with feed-forward path or with additional low-pass filters [35]), state feedback controllers [42], nonlinear controllers based on computational intelligence and hybrid controllers which combine approaches from other groups. However, in practice PID controllers (see e.g. [4]) are most commonly used. It results from a general knowledge of how they work and their relatively simple implementation in a microprocessor-based control system.

During controller design, engineer can modify PID parameters (i.e. tune controller) and he performs it if the need arises. It is important to point out that controller tuning is a difficult and time consuming process. Moreover, engineer based on his experience can modify the controller structure by means of trial-and-error method in order to obtain a better quality of control. Modification of controller structure causes the process of controller design much more difficult. Exemplary PID-based controller structures which were affected by this modification are shown in Fig. 1. The presented controllers, despite the differences in the structure, are used to perform the same control task, i.e. follow-up position control in the CNC machine tool [29], [41].

How we can see, the presented structures are slightly different. This is because there is no common and proved knowledge regarding which structure is superior and should be applied rather than others.

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Despite the fact that knowledge regarding control theory is widespread and well developed, the analytically obtained controller structures do not sufficiently take into account the impact of various disturbances (measurement, process, control, etc.) which are common in the real world. As a result, the common rule is that the human expert basing on his experience and applying the trial-and-error method have to improve the initial controller in order to obtain the satisfactory quality of control. In this paper it is proposed a method which allow to do this difficult and time consuming task automatically using an evolutionary algorithm (see e.g. [17,23,24,25,33,34,56,60]). In the literature thera are also many other nature-inspired algorithms, e.g. swarm algorithms (see [2,18,20,21,39]), however in this case classic evolutionary algorithm performs very well.

In our previous work [53] we dealt with the evolutionary selection (see e.g. [36,38,51]) of the structure and parameters of the control system (Fig. 2). The results encouraged us to develop a new approach. In this paper we propose a method for constructing more complex control systems. In this new approach we use first order infinite impulse response (IIR) input filters and extra feedforward paths (Fig. 3) in addition to standard PID blocks, which are typically used in a complex controller structure.

Please note that the proposed method can be successfully applied to all optimization problems which require not only parameters selection but also structure selection, e.g. structure selection of fuzzy systems (see e.g. [6,7,30]), neuro-fuzzy systems (see e.g. [11,14,16,15,47,49,50]), type-2 fuzzy systems (see e.g. [5,19,27,52]). Proposed algorithm may be also used in modelling (see e.g. [8,10,12,13,22,26,40,44,48]) and pattern recognition issues (see e.g. [43,45,55,57,58,59]).

This paper is organized into 4 sections. Section 2 contains an idea of using evolutionary method for optimization of the controller structure. Simulation results are presented in Section 3. Conclusions are drawn in Section 4.

2 Evolutionary Method for Designing the New Representation of the Controller Structure

In proposed method full controller (with its structure and parameters) is encoded in a single chromosome $\mathbf{X}_{ch}$. Chromosome $\mathbf{X}_{ch}$ is described as follows:

$$\mathbf{X}_{ch} = \left\{ \mathbf{X}_{ch}^{\text{par}}, \mathbf{X}_{ch}^{\text{red}} \right\}, \tag{1}$$

where $\mathbf{X}_{ch}^{\text{par}}$ is a chromosome encoding correction term parameters, $\mathbf{X}_{ch}^{\text{red}}$ is a chromosome encoding CB connection. Chromosome $\mathbf{X}_{ch}^{\text{par}}$ is described as follows:

$$\begin{aligned} \mathbf{X}_{ch}^{\text{par}} &= \left(a^1, K_P^1, T_I^1, T_D^1, a^2, K_P^2, T_I^2, T_D^2, \ldots, ff^1, \ldots, ff^4 \right) \\ &= \left(X_{ch,1}^{\text{par}}, X_{ch,2}^{\text{par}}, \ldots, X_{ch,L}^{\text{par}} \right), \end{aligned} \tag{2}$$

where $a^1, K_P^1, T_I^1, T_D^1, \ldots, ff^1 \ldots,$ denotes control system parameter values, $ch = 1, .., Ch$, denotes index of the chromosome in the population, Ch denotes a number of chromosomes in the population, L denotes length of the chromosome $\mathbf{X}_{ch}^{\text{par}}$. Chromosome $\mathbf{X}_{ch}^{\text{red}}$ is described as follows:

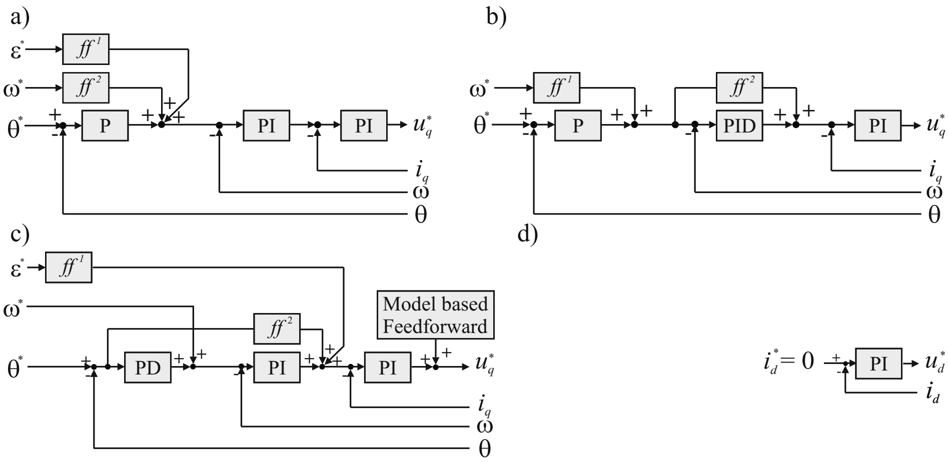

Fig. 1. Different controller structures a), b), c) used in industrial systems and d) common part of the PMSM servo-drive controller structure

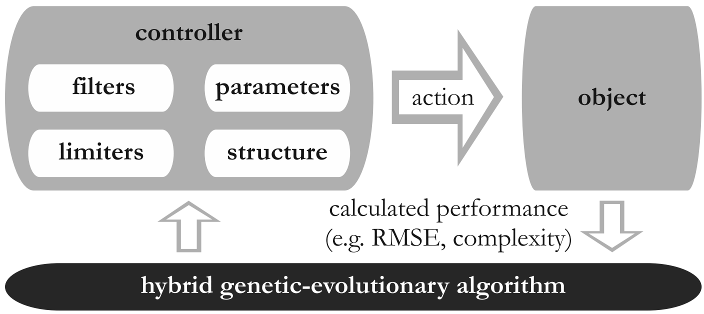

Fig. 2. Proposed idea of optimizing the controller using the evolutionary algorithm

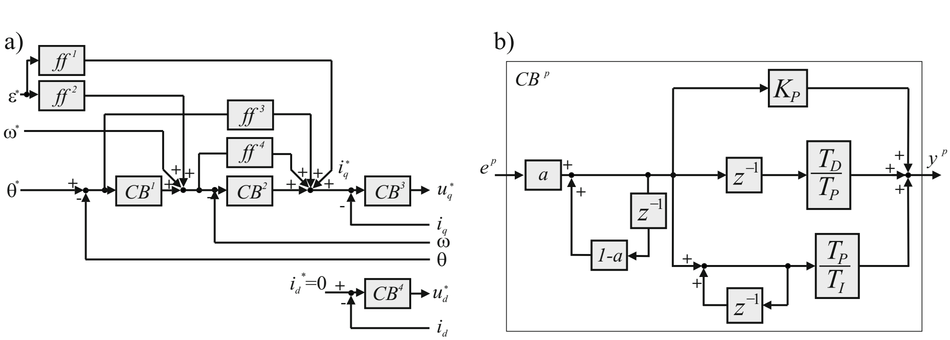

Fig. 3. The initial controller definition for the evolutionary algorithm

$$\mathbf{X}_{ch}^{\mathrm{red}} = \left(X_{ch,1}^{\mathrm{red}}, X_{ch,2}^{\mathrm{red}}, \ldots, X_{ch,L}^{\mathrm{red}}\right), \tag{3}$$

where every gene $X_{ch,g}^{\mathrm{red}} \in \{0,1\}$, $ch = 1,..,Ch$, $g = 1,..,L$, decides if relevant part of control system occurs in control process (relevant gene $X_{ch,g}^{\mathrm{red}} = 1$).

The steps of the method used in this paper are the same as in typical evolutionary algorithm ([3,9,28,31,32,46,54]). The evolutionary algorithm is a method of solving problems (mainly optimization problems) which is based on natural evolution. Evolutionary algorithms are searching procedures based on the natural selection and inheritance mechanisms. Steps of the method are following: chromosomes initialization, chromosomes evaluation, stop condition checking, chromosomes selection, chromosomes crossover, mutation and repair, offspring population generation. For more details see our previous papers, e.g. [53].

3 Simulations Results

3.1 Controlled Object

In our simulations it was considered a problem of design controller structure and parameters tuning for servo-drive with PMSM motor [1]. PMSM was modelled in a discrete form with time step T_s=10 μs and in state space representation as follows:

$$\begin{bmatrix} i_d^{k+1} \\ i_q^{k+1} \\ \omega^{k+1} \\ \theta^{k+1} \end{bmatrix} = \begin{bmatrix} 1 - T_s\frac{R}{L} & 0 & i_q T_s & 0 \\ 0 & 1 - T_s\frac{R}{L} & -T_s(i_d + \frac{\lambda_m}{L}) & 0 \\ 0 & 1.5 T_s P^2 \frac{\lambda_m}{J} & 1 - T_s\frac{F}{J} & 0 \\ 0 & 0 & T_s & 1 \end{bmatrix} \begin{bmatrix} i_d^k \\ i_q^k \\ \omega^k \\ \theta^k \end{bmatrix} + \begin{bmatrix} \frac{T_s}{L} & 0 \\ 0 & \frac{T_s}{L} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_d^k \\ u_q^k \end{bmatrix}, \tag{4}$$

where i_d, i_q, ω and θ are PMSM motor state variables, u_d, u_q is the input vector, i_d, i_q is the output vector. θ is angular position of the rotor flux, ω is its angular velocity. The i_d, i_q are direct and quadrature components (in a rotor reference frame) of electrical currents in the motor windings, while u_d, u_q are electrical voltages applied to the motor terminals. The motor model parameters are: R=1.456 Ω, L=0.008 H, λ_m=0.175 V·s, J=0.06 kg·m, F=0.001 N·m·s, and P=3.

Initial values of state variables (i_d, i_q, ω and θ) were set to zero. Simulation was carried out for time interval of 1.5s. A shape of the reference signal for the follow-up position control in the simulation with servo-drive controller was defined as follows

$$\theta^* = 100 \cdot \left(1 + sin\left(\frac{t}{1.5} \cdot \Pi - \frac{\Pi}{2}\right)\right), \tag{5}$$

and it is also presented in Fig. 4. According to practical reasons (i.e. the physical limitation of the actuators) output signal of each CB was limited. Output of CB^1, CB^2, CB^3 and CB^4 was limited to values 100 rad/s, 20 A, 350 V and 350 V

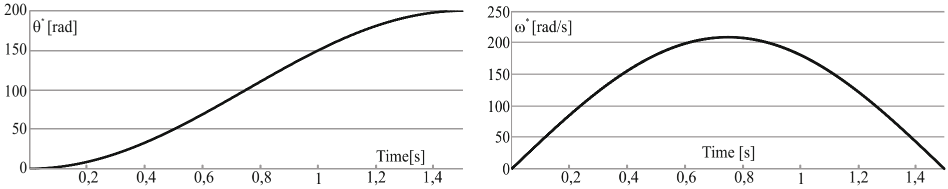

Fig. 4. Angular position (θ) and velocity (ω) reference values

respectively. Moreover, limited resolution of position and motor current sensors was the cause of quantization for the input signals (θ, ω, i_d and i_q) to values $0.628 \cdot 10^{-3} rad$ (10000 pulse per rev.), 0.314 rad/s, 0.01 A and 0.01 A (4096 ADC voltage levels) respectively. Quantization resolution for the output signal (u_d^* and u_q^*) was set to value 0.07V (5000 levels) because of the limited resolution of the pulse width modulation (PWM) module. Time interval between subsequent controller activations was set to 100 μs which is a reasonable value for today microprocessor systems.

3.2 Controller Design

Initial controller definition is presented in Fig. 3. Search range for parameters contained inside each CB block (a, K_P, T_I, T_D) and for feedforward gain (ff) was set experimentally. Search ranges were set as follows: K_P=<0,300>, T_I=<10^{-6},1>, T_D=<0,10^{-3}>, a=<0.1,1> and ff=<0,200>. On the basis of the assumption of the vector control algorithm symmetry, the values of the CB^4 block parameter were copied from the values obtained for block CB^3 and therefore they were not tuned separately.

3.3 Hybrid Evolutionary Algorithm

Controller structure definition and parameter tuning were performed using hybrid evolutionary algorithm. Algorithm was executed with following settings: the number of chromosomes in the population was set to 50, the algorithm performs 5000 steps (generations), the crossover probability was set as 0.99, the mutation probability was set as 0.3, the mutation intensity was set as 0.3. the fitness function with weights was defined as follows:

$$\text{ff}(\mathbf{X}_{ch}) = \begin{pmatrix} MSE^1_{ch} \cdot w_1 + MSE^2_{ch} \cdot w_2 + MSE^3_{ch} \cdot w_3 + MSE^4_{ch} \cdot w_4 + \\ os^{u_q}_{ch} \cdot w_{os} \end{pmatrix}. \quad (6)$$

MSE^1_{ch} error function of the ch chromosome is described by the following formula:

$$MSE^p_{ch} = \frac{1}{N} \cdot \sum_{j=1}^{N} (e^p_{ch,j})^2, \quad (7)$$

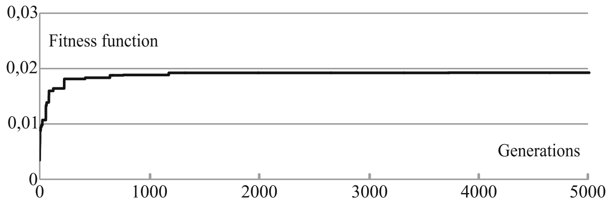

Fig. 5. The process of controller structure search by means of the evolutionary algorithm

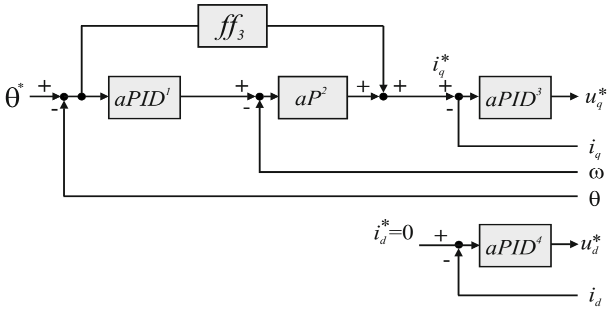

Fig. 6. Controller structure obtained by means of hybrid evolutionary algorithm

Table 1. Parameter values of CB terms obtained by means of hybrid evolutionary algorithm

K_P^1	T_I^1	T_D^1	a^1	K_P^2	a^2
38.48	$175.4 \cdot 10^{-6}$	$623.0 \cdot 10^{-6}$	0.6015	29.80	0.0796
K_P^3	T_I^3	T_D^3	a^3	ff^3	
48.77	$29.59 \cdot 10^{-6}$	$735.4 \cdot 10^{-6}$	0.6891	1.977	

where e^p denotes error value on CB^p input, $j = 1, \ldots, N$, denotes sample index, N denotes the number of samples, $p = 1 \ldots, 4$ denotes CB-index, and $e^1_{ch,j}$ is defined as follows:

$$e^1_{ch,j} = \theta^*_j - \theta_{ch,j}, \tag{8}$$

while $e^2_{ch,j}$, $e^3_{ch,j}$, $e^4_{ch,j}$ are defined as it is shown in Fig. 3. Value of the $os^{u_q}_{ch,j}$ is defined as a number of oscillations of the signal u_q, which is feed to the actuator. Existence of large number of oscillation with amplitude higher than experimentally chosen value can cause negative increase of the noise level generated by the PMSM motor. The number of oscillations should be reduced.

The fitness function weights were set as follows: w_1=194.4, w_2=33.43, w_3=1229, w_4=62518 and w_{os}=$4.383 \cdot 10^{-4}$. Process of controller structure search is presented in Fig. 5.

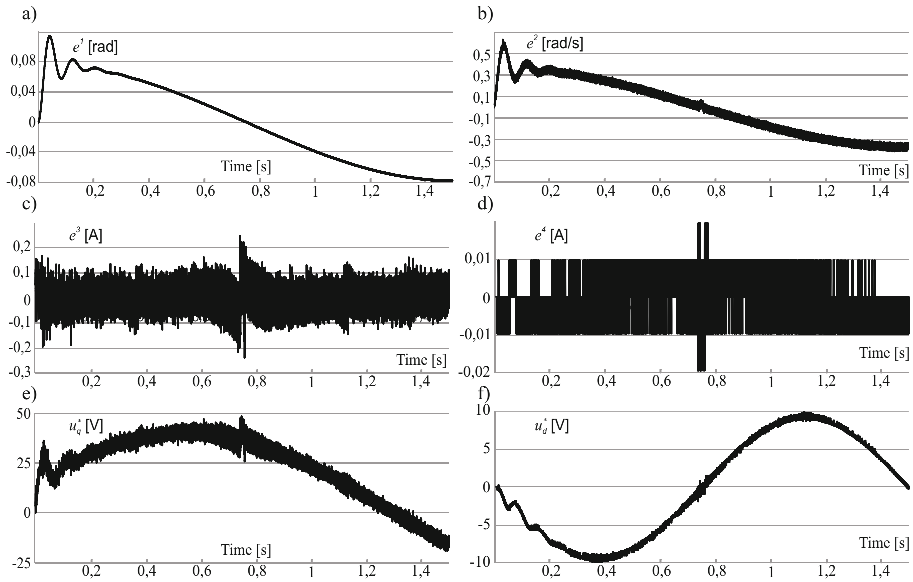

Fig. 7. Values on the input of: a) position, b) velocity, c) current i_d, b) current i_q controller. Values of the : e) voltage u_q, f) voltage u_d signal

3.4 Search Results

Controller structure obtained by means of hybrid evolutionary algorithm is presented in Fig. 6. Parameters of structure obtained by means of hybrid evolutionary algorithm are presented in Table 1, while its performance is presented in Fig. 7.

Control problem presented in this paper confirms application of one (ff^3) feed-forward path, as presented in controller structure in Fig. 3. Values of parameters a^1, a^2 and a^3 lower than one confirm application of first order IIR filter.

As we can see in Fig. 7.a, the position error (e^1) is relatively high, i.e. about 0.1 rad. In some applications it can be an unacceptable value. However, it was confirmed by the experiment that it is possible to reduce the position controller error to level as low as 0.002 rad. This can be obtained by proper setting of fitness function weight $(w_1, \ldots, w_5)$, although it causes an negative increase of the noise level generated by the PMSM motor. Setting of mentioned weights relies on the human designer of the control system.

Simulation results can be summarized as follows: quality of evolutionary designed controller structure as presented in Fig. 7 is acceptable. Obtaining and tuning of similar controller structure by means of typical methods would be daunting.

4 Summary

In this paper the approach to selection of controller structure equipped with feed-forward signals and filter terms by means of hybrid evolutionary algorithm was suggested. In performed simulations the correctness of suggested method was confirmed.

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