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Control system synthesis by means of Cartesian Genetic Programming

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Abstract

Cartesian Genetic Programming (CGP) is a type of Genetic Programming based on a program in a form of a directed graph. It also belongs to the methods of Symbolic Regression allowing to receive the optimal mathematical expression for a problem. Nowadays it becomes possible to use computers very effectively for symbolic regression calculations. CGP was developed by Julian Miller in 1999-2000. It represents a program for decoding a genotype (string of integers) into the phenotype (graph). The nodes of that graph contain references to functions from a function table, which could contain arithmetic, logical operations and/or user-defined functions. The inputs of those functions are connected to the node inputs, which itself could be connected to a node output or a graph input. As a result, it's possible to construct several mathematical expressions for the outputs and calculate them for the given inputs. This CGP implementation use point mutation to form new mathematical expressions. Steady-state genetic algorithm is chosen as a search engine. Solution solving the control system synthesis problem is presented in a form of the Pareto set, which contains a set of satisfactory control functions. Nonlinear Duffing oscillator is taken as a dynamic object.

Keywords: Optimal control synthesis, nonlinear control systems, Cartesian Genetic Programming, genetic programming

1. Introduction

There are definite problems connected with control system synthesis for a non-linear dynamic object. And one of them is complexity and often impossibility to define control function by analytical methods. However, with the rapid

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advancements in computer technologies and development of new methods and algorithms such problems are successfully solved by numerical methods of symbolic regression. Cartesian genetic programming belongs to these methods.

2. Problem statement

The synthesis problem is formulated as a search problem of control function from the object state [1].

A mathematical model of the control object is given in a form of a system of ordinary differential equations:

$$\dot{\mathbf{x}} = \mathbf{f}\left(\mathbf{x}, \mathbf{u}\right), \tag{1}$$

Here, $\mathbf{x} = \left[x_1 \cdots x_n\right]^T$ - state vector of the control object, $\mathbf{x} \in \mathbf{R}^n$, $\mathbf{u} = \left[u_1 \cdots u_m\right]^T$ - control vector, $\mathbf{u} \in \mathrm{U} \subseteq \mathbf{R}^m$, $m \le n$, U - closed limited set.

Initial conditions:

$$\mathbf{x}^0 \subseteq \mathbf{R}^n,\ \mathbf{x}\left(0\right) = \mathbf{x}^0 = \left[x^{0,1} \ldots x^{0,k}\right]^T \tag{2}$$

The terminal conditions are given in a form of $n-r$ dimensional diversity:

$$\phi_i\left(\mathbf{x}\left(t_f\right)\right) = 0,\ i = \overline{1,r} \tag{3}$$

Quality functional:

$$J = \int_0^{t_f} F_0\left(\mathbf{x}\left(t\right), \mathbf{u}\left(t\right)\right) dt \to \min \tag{4}$$

t_f - the duration of the control process

$$t_f = \begin{cases} t, x(t) \in \mathbf{x}^f \\ t^+, x(t) \notin \mathbf{x}^f \end{cases} \tag{5}$$

t^+ - given upper level of the acceptable control time.

It is necessary to synthesize a control system in the following form:

$$\mathbf{u} = \mathbf{g}\left(\mathbf{x}, \mathbf{q}\right),\ \mathbf{g}\left(\mathbf{x}, \mathbf{q}\right):\ \mathbf{R}^n \to \mathbf{R}^m, \tag{6}$$

$\mathbf{q} = \left[q_1 \cdots q_R\right]^T$ is a vector of control system parameters, $\mathbf{q} \in \mathrm{Q} \subseteq \mathbf{R}^R$, where Q is a limited set. Moreover, the resulting control system should provide a minimum of the functional (4) and satisfy the terminal conditions:

$$\mathbf{x}\left(t_f\right) \in \mathbf{x}^f, t_f \le t^+ \tag{7}$$

and control bounds of system (1):