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A Novel Hybrid Fuzzy PID Controller Based on Cooperative Co-evolutionary Genetic Algorithm

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ABSTRACT

Conventional PID controllers are still used in industry due to their simplicity in structure, and ability to eliminate steady state error in operating point. However, it is difficult to achieve a desired tracking control performance since for highly non-linear processes. In order to improve the set point tracking performance under aforementioned issues, a novel hybrid fuzzy PID controller is proposed in this paper. The proposed method is consists of a fuzzy PD controller and also a conventional PID controller that are responsible for handling non-linear and linear regions of the control system, respectively. Moreover, a bumpless transfer that aims to minimize the jump at the instant of switching between two controllers is considered. Finally, cooperative co-evolutionary algorithm is used to tune hybrid scheme, and results show better response in terms of convergence speed when compared to the traditional genetic algorithm evolution approach.

KEYWORDS: FLC, hybrid fuzzy PID, evolutionary algorithm, genetic algorithm, CSTR.

1. INTRODUCTION

It is well known that, a conventional proportional integral-derivative (PID)-type controllers are still used in industrial application due to their simplicity in structure, ease of design, and inexpensive cost [1, 2]. PID controllers have acceptable ability to reduction or elimination of steady state error and disturbance rejection in vicinity of the system equilibrium point; however, it is difficult to achieve a desired tracking control performance if a controlled object is highly non-linear, and uncertainties exist in control system [3].

Recently, with the increasing research activities in the field of nonlinear control, many control methods have been developed. These methods are nonlinear model predictive control, gain scheduling, sliding mode control, fuzzy control, etc. [4]. Fuzzy logic as an intelligent computation has been used in the various area of investigations [5, 6]. Fuzzy Logic Controller (FLC) emulates human behavior in control via rule base system. The FLCs are more suitable for nonlinear plants where it is difficult to control with conventional controllers such as PID controllers [7]. The development of fuzzy PID controllers need the construction of a three-dimensional rule base, which makes its design very complicated in terms of rule base structure and implementation of inference engine [8]. Usually, instead of using fuzzy PID controller with three-dimensional rule base, fuzzy PD or fuzzy PI controllers have been used. In general, a fuzzy PI controller gives a poor performance during transient time for nonlinear system due to the integration operation, while a fuzzy PD controller has a difficulty in removing the system steady-state error [9, 10].

Recently hybrid fuzzy logic control approach is used in control applications in which conventional PID controller and FLC have been combined by blending mechanism that depends on a certain function of actuating error [11]. Hybridization of these two controller structures utilizes the advantages of both controllers. According to reference [9], a hybrid method has been proposed that directly switches between fuzzy PD controller and PID controller. This direct switch may produce non-smooth control action that is undesirable in practice. Also in [9], expert's experience and knowledge method has been used to design membership functions and fuzzy rule base. In knowledge method-based, however a common challenge is encountered in the derivation of fuzzy rules and associated membership functions, which is often time consuming based on trial-and-error, and relies on expert knowledge [12, 13].

In this paper, a procedure for designing hybrid fuzzy PID controller based on cooperative co-evolutionary algorithm is proposed. Cooperative co-evolutionary algorithm is used to automate tuning the coefficients of PID controller, and also free parameters of each fuzzy rule in fuzzy PD controller. Furthermore, a bumpless transfer is considered for producing smooth control action.

The remainder of this paper is organized as follows. In Section 2, we explain the structure of the fuzzy logic controller. Section 3, completely explains hybrid control scheme. In section 4 a brief review of the cooperative co-

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evolutionary is presented, while in the last section, we show the effectiveness of the hybrid controller on the case of the CSTR.

2. FUZZY INFERENCE SYSTEM

In this research, a first-order TSK-type fuzzy inference system (FIS) is used as the fuzzy PD controller. A schematic of the first-order TSK- type fuzzy inference system [14, 15] with two inputs is shown in Fig. 1.

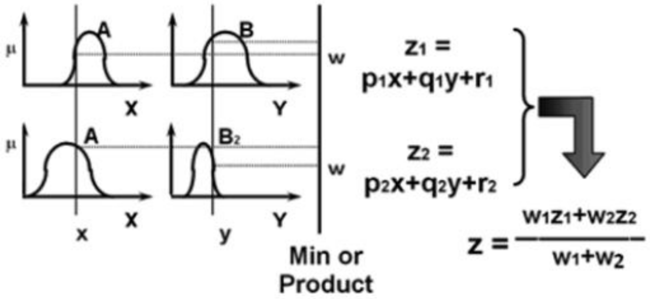

Fig. 1. A scheme of a first order TSK-type FIS [15].

Such fuzzy system is composed of the several IF-THEN rules. Each fuzzy rule includes two main parts: antecedent and consequent. Antecedents contain linguistic values that are defined with membership functions, and the consequent of rule is a linear crisp function of inputs value. The *i*th rule, denoted as R_i , in the FS is represented in the following form:

$$R_i : \text{If } x_1 \text{ is } A_{i1} \text{ And} \dots \text{And } x_n \text{ is } A_{in}, \text{ Then u is } z_i = a_n x_n + a_{n-1} x_{n-1} + \cdots a_0 \qquad (1)$$

where, $x_1,\dots, x_n$ are input variables, u is the system output variable, A_{ij} and z_i , j=1…n, are respectively, fuzzy sets associated with the n*th* fuzzy input variables, and output of *i*th rule. Fuzzy set A_{ij} uses a Gaussian membership function as:

$$\mu_{A_{ij}}(x_j) = exp\left(-\left(\frac{x_j - c_{ij}}{\sigma_{ij}}\right)^2\right), \qquad (2)$$

where c_{ij} and σ_{ij}, that are adjustable parameters, represent the center and width of the fuzzy set A_{ij}, respectively, and $\mu_{A_{ij}}$ is the grade of the membership function of A_{ij}. If there are *r* rules in a FS and given the input x= $[x_1,\dots, x_n]$, the output of the fuzzy system is calculated by the weighted average defuzzification method as follows:

$$u = \frac{\sum_{i=1}^{r} \varphi_i(\bar{x}) z_i}{\sum_{i=1}^{r} \varphi_i(\bar{x})} \qquad (3)$$

where the firing strength $\varphi_i(\bar{x})$ of the i*th* rule is calculated as:

$$\varphi_i(\bar{x}) = \prod_{j=1}^{n} \mu_{A_{ij}}(x_j). \qquad (4)$$

3. HYBRID FUZZY-PID CONTROLLER

There are still difficulties in the design of FLC. One of the important problems involved with the design of FLC is its complexity. As mentioned before it is common to use the fuzzy PD or PI instead of fuzzy PID that each have own limitations. The hybrid of FLC and PID controllers takes advantages of the nonlinear characteristics of the FLC and the simplicity and accuracy of conventional PID controller.

The Architecture of the proposed hybrid controller is shown in Fig. 2. The essential part of proposed control structure is the switching mechanism. It provides two control modes that depends on a defined threshold of error; namely, fuzzy control mode and PID control mode. Moreover, a bumpless transfer is integrated to it that produce a smooth control action.

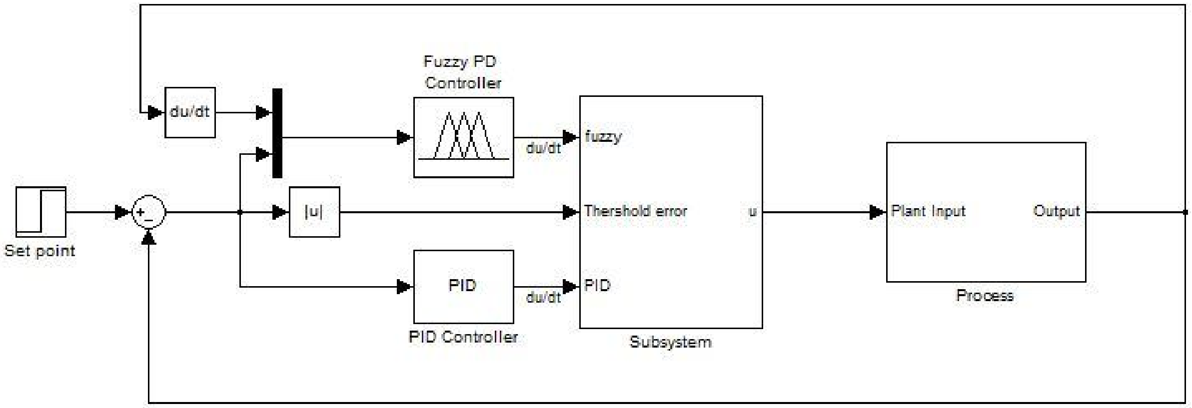

Fig. 2. The Simulink model of hybrid control system.

A switch firstly decides which one of the two controller structures is selected based on actuating error. Actuating error is computed as absolute error between set point and output of the control system. If the actuating error is higher than the threshold error (e_{th}), the hybrid method applies the fuzzy PD controller, which handles nonlinear control of the controlled system and has a fast rise time. When the actuating error is below the e_{th}, the hybrid method switches to the PID controller, which has better steady-state error elimination.

In our method, both fuzzy PD and PID controllers are based on velocity form. In velocity form controller compute change (velocity) of the control variable. The control variable is then simply obtained by integrating its change. This form of controllers is suitable for implementing of anti wind-up protection and bumpless transfer methods. A PID controller in the velocity form [16] is shown in Fig. 3.

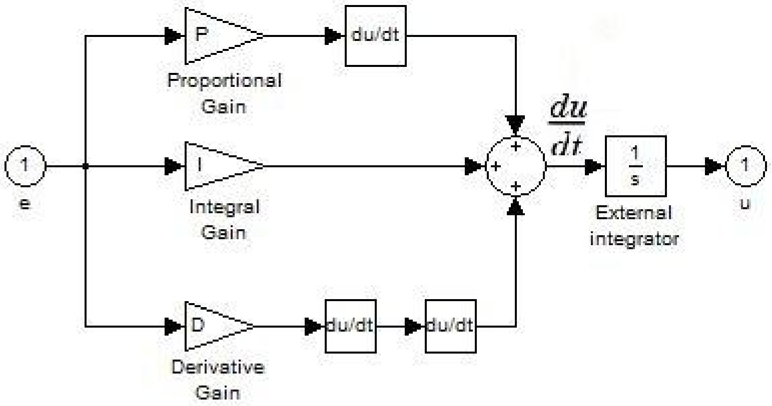

Fig. 3. Block diagram of a PID algorithm in velocity form.

3.1 BUMP TRANSFER AND BUMPLESS TRANSFER

Peng et al. [17], discussed the switching between manual and PID control modes. Consider the control scheme presented in Fig. 4. According to [17] the bump transfer phenomenon can be defined as follows*: "Assume that the switch goes from automatic to manual control. If* Um *is such that for some time e > 0, then the integral term increases in an uncontrolled way to very high values and* U *becomes high and much greater than* Um. *Now, assume that the switch goes back from manual to automatic control. At that moment, even if e = 0, a big jump occurs at* Ur, *due to the high values of the integral term. Moreover,* U *decreases only if e < 0 for a sufficiently long time. This leads to a long settling time of the process output."* This mode switching with a jump at the control action (Ur) has been called bump transfer. To eliminate the jump, the controller output U should be made as close as possible to Um during manual mode. This mode switching has been called bumpless transfer.

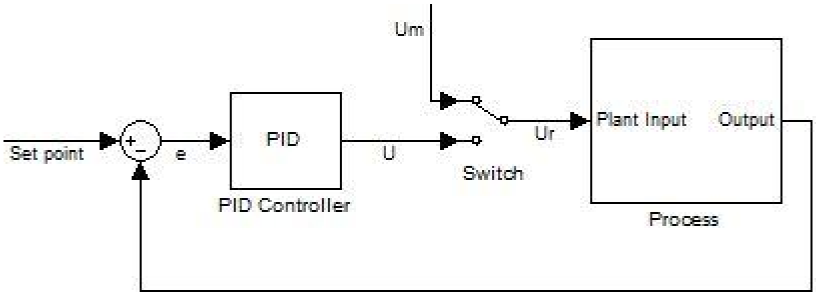

Fig. 4. Bump transfer from manual to automatic mode [17].

To avoid bump transfer (switching transient) in proposed control structure, it is necessary to make sure that the integrator associated with PID controller is reset to a proper value when the hybrid control is in fuzzy PD control mode. Similarly, the integrator associated with fuzzy PD controller must be reset to a proper value when the controller is in PID control mode. This can be realized with the circuit shown in Fig. 5. When the hybrid control operates in fuzzy PD control mode the feedback from the output *v* of the PID controller tracks the output *u*. With efficient tracking the signal *v* will thus be close to *u* at all times. There is a similar tracking mechanism that ensures that the integrator in the fuzzy PD controller tracks the output u.

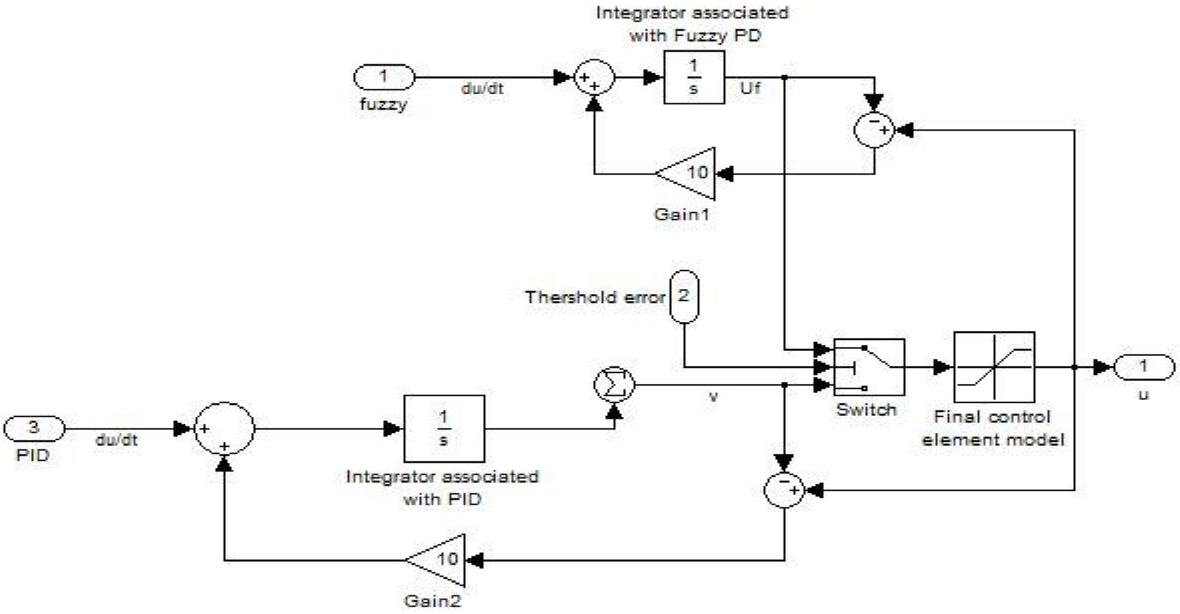

Fig. 5. Bumpless Transfer model.

4. COOPERATIVE CO-EVOLUTIONARY ALGORITHM

Co-evolutionary algorithms [18, 19] are advanced evolutionary techniques proposed to solve decomposable complex problems. They involve two or more species (populations) that permanently interact among them by a coupled fitness. Each species represents a subcomponent of a potential solution. Complete solutions are obtained by assembling representative members (cooperators) of each of the species. The fitness of each individual depends on the quality of (some of) the complete solutions it participated in, thus measuring how well it cooperates to solve the problem. The evolution of each species is controlled by a separate, independent genetic algorithm. This co-evolution makes easier to find good solutions to complex problems. The use of cooperative co-evolutionary algorithms is recommendable when the following issues arise [20]:

1. The search space is huge,
2. The problem may be decomposable in subcomponents,
3. Different coding schemes are used, and
4. There are strong interdependencies among the subcomponents.

The general cooperative co-evolutionary framework for S species is illustrated in Fig. 6. A more detailed view of the fitness evaluation process was explained in these Refs [19, 20, and 21].

The cooperative co-evolutionary approach performs better than single-population evolutionary algorithm, and also requires less computation because populations involved are smaller, and convergence, in terms of number of generations, is faster. Because of these advantages, all free parameters ($c_{ij}, \sigma_{ij}, and\ a_n$) in fuzzy controller and PID (PID gains) controller will be optimized by genetic cooperative co-evolutionary algorithm.

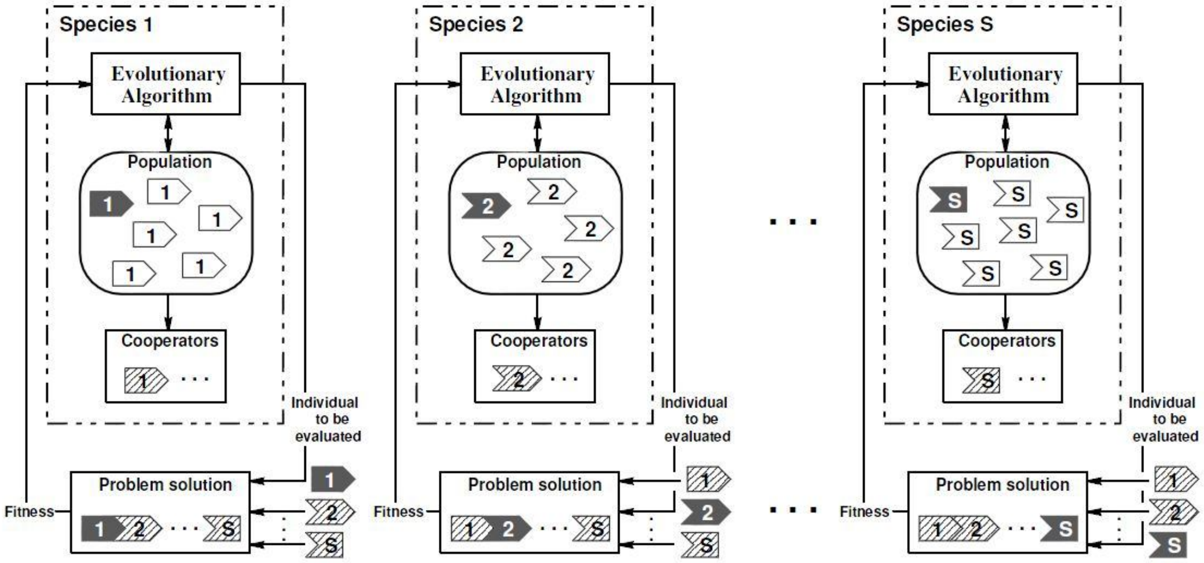

Fig. 6. Cooperative co-evolutionary framework for S species [19].

5. SIMULATION RESULTS

The hybrid scheme described in section 3 has been applied to a CSTR to verify that the scheme has a good performance for a dynamic system.

5.1 THE CSTR MODEL

The case of a non-isothermal CSTR is considered here. The reactor is a non-isothermal CSTR with irreversible reaction (A ⟶ B). The heat of reaction is removed via the cooling jacket that surrounds the reactor. The reactor and the jacket cooling water are assumed to be perfectly mixed. The reactor model equations are obtained by a component mass balance and energy balance principle:

$$\frac{dC_A}{dt} = \frac{F}{V_R}(C_{A0} - C_A) - V_R C_A k_0 e^{-E/RT_R} \qquad (5)$$

$$\frac{dT_R}{dt} = \frac{F}{V_R}(T_0 - T_R) - \frac{\lambda C_A k_0 e^{-E/RT_R}}{\rho c_p} - \frac{UA_J(T_0 - T_0)}{V_R \rho c_p} \qquad (6)$$

$$\frac{dT_J}{dt} = \frac{F_J}{V_J}(T_{C,in} - T_J) + \frac{UA_J(T_R - T_J)}{V_J \rho_J c_J} \qquad (7)$$

Where F_J is the cooling water as the manipulated variable, while C_A, T_R, and T_J are concentration, reactor temperature and jacket temperature respectively. The objective is to control the temperature of tank by manipulating F_J. All parameters are shown in Table 1.

Table 1: Irreversible exothermic reaction parameters [22].

Preexponential factor k_0	s^{-1}	$20.75\ \times 10^6$
Activation energy E	$J/kmol$	$69.71\ \times 10^6$
Process molecular weight	$kg/kmol$	100
Process densities $\rho_0$and ρ	kg/m^3	801
Coolant density ρ_J	kg/m^3	1000
Process heat capacities c_{p0} and c_p	$J\ kg^{-1}\ K^{-1}$	3137
Coolant heat capacity c_J	$J\ kg^{-1}\ K^{-1}$	4183
Heat of reaction λ	$J/kmol$	$-69.71\ \times 10^6$
Feed temperature T_0	K	294
Feed composition C_{A0}	$kmol/m^3$	8.01
Inlet coolant temperature $T_{C,in}$	K	294

5.2 RESULTS AND DISCUSSION

1. Threshold error set to 0.5.
2. Nine rules are considered in fuzzy PD controller.
3. The input variables of the fuzzy PD controller are error, e(t) between the measured reactor temperature and the set point, and error derivation $\dot{e}(t)$; the universe of discourse e and $\dot{e}(t)$ are normalized to [-1, 1].
4. The cost function is well known Mean Square Error (MSE).
5. Ten species is considered in cooperative co-evolutionary algorithm; one species for PID coefficients, and nine species for the fuzzy PD controller rules.

The parameters of GA were specified as:
Population size in each species = 10,
Generations= 15,
Crossover probability= 0.6,
Mutation probability= 0.2.

We evaluated cooperative co-evolutionary GA by comparing its performance with the performance of a traditional GA on the CSTR control problem. The co-evolutionary and traditional GA differ only as to whether they utilize multiple species as described in the previous section. All other aspects of the algorithms are equal and are held constant.

The progress curve of the traditional and co-evolutionary algorithms is shown in Fig. 7. The horizontal axis is in the number of objective function evaluations for fair comparison since the evaluation is the dominant operation in the evolution algorithm. The average objective functions over five runs are plotted for each algorithm. The fact that the average objective function of the co-evolutionary algorithm is smaller than traditional algorithm indicates that proposed optimization algorithm has superior rate of convergence over the traditional evolutionary algorithm. It is to be noted that the cooperative co-evolutionary approach continues to improve the objective function even after the traditional GA has ceased to improve. Traditional GA appears to be prematurely convergent despite its great descent performance at the beginning. Also, performance of the best solution found by co-evolutionary approach has been illustrated in Fig. 8.

6. CONCLUSIONS

In this paper, a new approach toward optimal design of a hybrid PID controller using cooperative co-evolutionary algorithm has been presented. In control structure a bumpless transfer is introduced that prevents from plant input jump at the instant of switching. The performance of the proposed hybrid controller was evaluated by simulation study on a temperature control of CSTR. The simulation results show that the performance of the FLC designed by our approach is fairly good.

As future work, it is necessary to further prove effectiveness of the proposed algorithm applied to other problems. The generality of the technique opens up a wide range of potential applications. There also remains the need for additional study on the trade-off between the number of rules used and the resulting system performance.

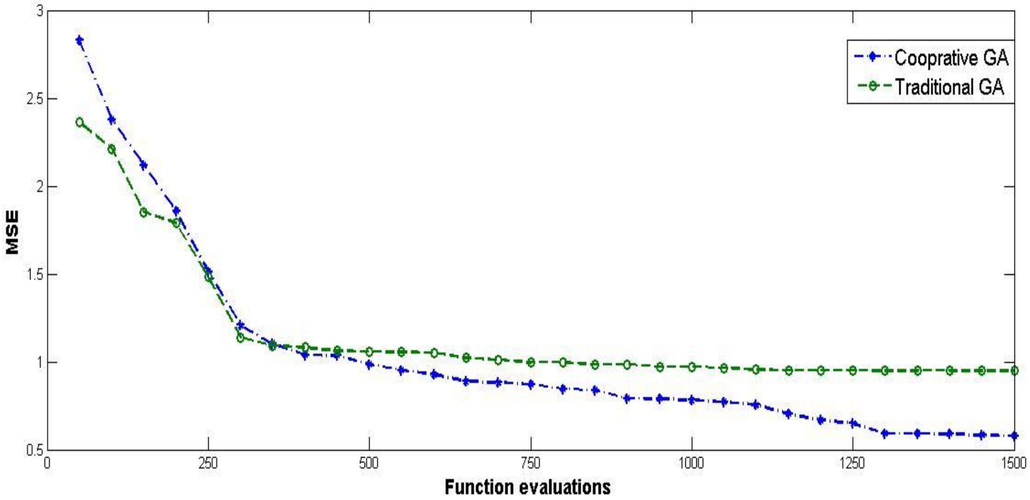

Fig. 7. Comparisons of traditional GA and co-evolutionary GA performance.

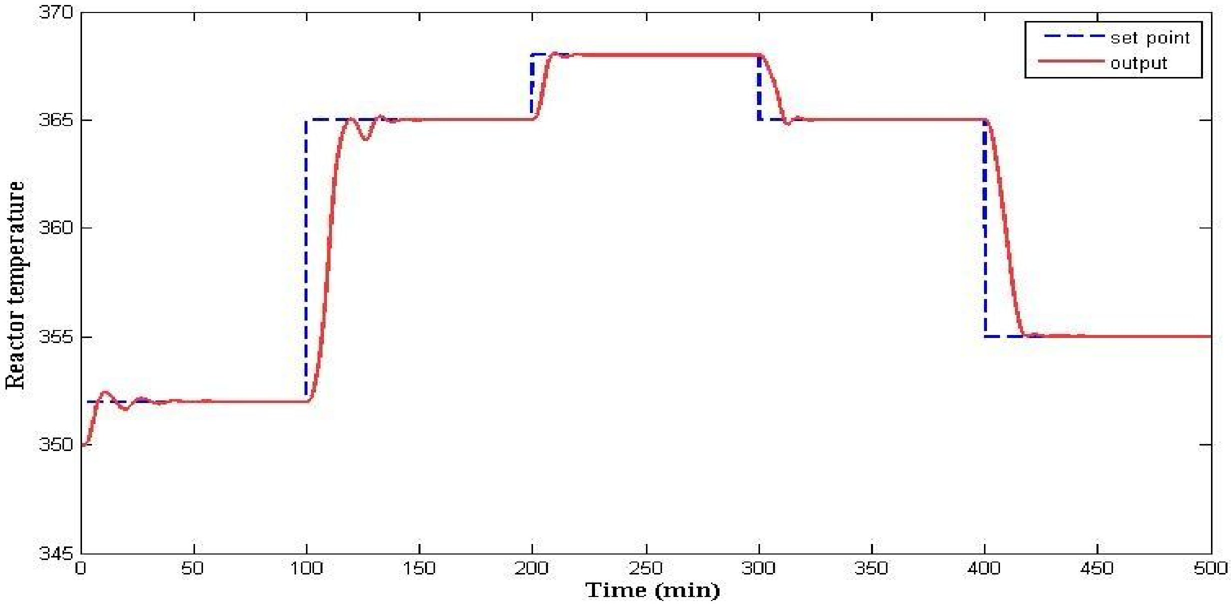

Fig. 8. Reference tracking of the optimized hybrid controller.

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