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Design of optimized cascade fuzzy controller based on differential evolution: Simulation studies and practical insights

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ABSTRACT

In this study, we discuss a design of an optimized cascade fuzzy controller for the rotary inverted pendulum system and ball & beam system by using an optimization vehicle of differential evolution (DE). The structure of the differential evolution optimization environment is simple and a convergence to optimal values realized here is very good in comparison to the convergence reported for other optimization algorithms. DE is easy to use given its mathematical operators. It also requires a limited computing overhead. The rotary inverted pendulum system and ball & beam system are nonlinear systems, which exhibit unstable motion. The performance of the proposed fuzzy controller is evaluated from the viewpoint of several performance criteria such as overshoot, steady-state error, and settling time. Their values are obtained through simulation studies and practical, real-world experiments. We evaluate and analyze the performance of the proposed optimal fuzzy controller optimized by Genetic Algorithm (GA), and DE. In this setting, we show the superiority of DE versus other methods being used here as well as highlight the characteristics of this optimization tool.

1. Introduction

Most industrial plants exhibit a substantial level of nonlinearity and uncertainty. They pose difficulties from the perspective of control engineering and the design of controllers, in particular. In order to overcome these difficulties in the design of a controller, various architectures have been developed whose construction are supported by pertinent algorithms. Over the past decade, we have witnessed a rapidly growing interest in fuzzy control in application to nonlinear systems, and many successful applications have been reported with anticipation that such a technology could be efficiently utilized in numerous challenging control problems (Chang, 2009; Chiou and Liu, 2009; Choi et al., 2008; Coupland and John, 2007; Hagras, 2004).

Fuzzy control is one of the useful control paradigms for uncertain and ill-defined nonlinear systems (Oh, 2002; Oh et al., 2004). Control actions of a fuzzy controller are described by some linguistic rules. This property makes the control algorithm easy to comprehend. However, it is not easy to determine numeric values of the parameters of the fuzzy controller leading to good performance.

The rotary inverted pendulum system is a classical control example used to stabilize an inherently unstable system. The rotary inverted pendulum is also an accurate model in the pitch and yaw of a rocket in flight and as such can be used as a benchmark for many useful control methodologies (Grasser et al., 2002; Ortega et al., 2002; Reza, 2001). The basic control objective of the rotary inverted pendulum system is to stabilize the pendulum around the unstable equilibrium point (viz. the upright position).

The ball & beam system is viewed as a benchmark control engineering setup whose underlying concept can be applied to stabilization problem for diverse systems such as the balance problem dealing with goods to be carried by moving robot and spaceship position control systems in aerospace engineering, refer to (Chang et al., 1998; Glower and Munighan, 1997; Hauser et al., 1992; Wang, 1998).

Fuzzy control is one of the useful control techniques to deal with uncertain and ill-defined nonlinear systems. Control actions of the fuzzy controller are realized by executing some linguistic rules. The rules themselves contribute to a significant interpretability of the controller (Oh et al., 2004; Tong et al., 2002). In this study, we introduce a fuzzy PD cascade controller scheme to control both pendulum and ball & beam system.

Genetic algorithms (GAs) are well-known as an optimization algorithm, which can be used to search global solution (Jin, 2002; Michalewicz, 1996). They have been shown to be very successful

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in many applications and in very different domains. However it may get trapped in a sub-optimal region of the search space thus becoming unable to find better quality solutions, especially for irregular and large search space. The ongoing challenge for advanced system control has resulted in a diversity of design methodologies and detailed algorithms. One of the difficulties in controlling complex systems is to derive the optimal values of control parameters such as linguistic control rules and scaling factors and membership functions of the fuzzy controller. Optimal control parameters have an immediate influence on the performance of fuzzy controller. It is difficult to assume that the given expert's knowledge captured in the form of the rules of the fuzzy controller leads to optimal control (Jamaludin et al., 2009; Mohan and Arpita, 2008). To improve the performance of the controller through adjusting control rules and membership functions one has to seek some optimization vehicle such as e.g., particle swarm optimization, tabu search, or genetic algorithms (Denna et al., 1999). Genetic algorithms have emerged as a sound optimization technique however they are not free from shortcomings. Conventional serial genetic algorithms (SGAs) come with premature convergence problem, which is associated with the reduced diversity of chromosomes occurring in successive generations of the algorithm.

DE suggested initially for solving the Chebychev polynomial fitting problem is similar to genetic algorithm (GA) including crossover, mutation and selection process. However, differential evolution algorithm is simpler than GA because it uses a vector concept in populating process.

In this paper, we propose an optimized fuzzy controller developed with the use of differential evolution (DE) for both rotary inverted pendulum system and ball beam system. The proposed fuzzy controller is based on the design methodology of cascade controller control system. When designing fuzzy controllers, it is difficult to determine values of the control parameters that are usually obtained by a large of trial-and-error experimentation or by exploiting experience of human experts. Therefore, we propose a new approach to determine optimal parameters of the fuzzy controller using DE. We offer a thorough comparison of the results of experiments for the controller constructed by making use of GAs.

2. A mathematical model of the inverted rotary pendulum

The rotary inverted pendulum system is shown in the Fig. 1. The inverted pendulum system is composed of a pendulum, rotating arm, potentiometer, and a motor. We defined that positive direction of rotating arm is to be counterclockwise and positive direction of pendulum is to be clockwise. The rotary inverted pendulum can be represented as a system with one input V_m (voltage of the motor), and two outputs: α (angle of the pendulum) and θ (angle of the rotating arm). The equations of motion for inverted pendulum come in the form of the Euler–Lagrange equations expressing a total potential and kinetic energy.

Nonlinear equations of motion are presented below. In the sequel, linearized equations of motion will be provided as well. Those are obtained by substitutions $\cos(\alpha)=1$ and $\sin(\alpha)=\alpha$ in the original nonlinear equations. The values of the parameters of the system are reported in Table 1.

$$(J_{eq}+mr^2)\ddot{\theta}-mLr\cos(\alpha)\ddot{\alpha}+mLr\sin(\alpha)\dot{\alpha}^2=T_{output}-B_{eq}\dot{\theta} \quad (1)$$

$$\frac{4}{3}mL^2\ddot{\alpha}-mLr\cos(\alpha)\ddot{\theta}-mgL\sin(\alpha)=0 \quad (2)$$

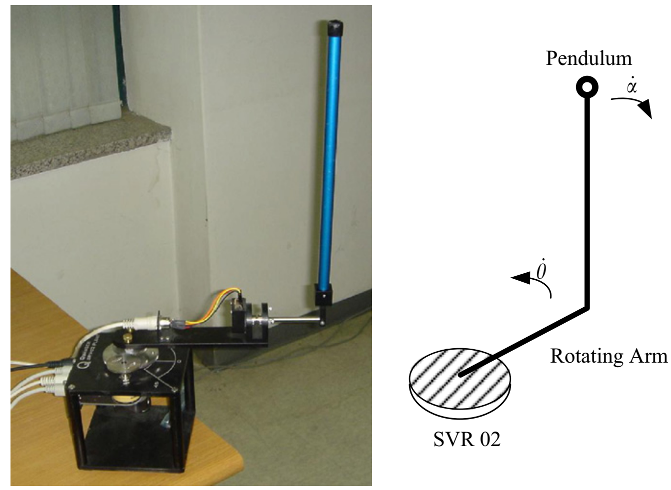

Fig. 1. Rotary inverted pendulum system.

Table 1
Rotary inverted pendulum and its parameters.

Parameter	Description
$J_{eq}=0.0036$	Equivalent inertia as seen at the load (kg m^2)
$B_{eq}=0.004$	Equivalent viscous damping coefficient as seen at the load (N m s/rd)
$r=0.158$	Length of rotating arm (m)
$m=0.125$	Mass of pendulum (kg)
$L=0.168$	Length of pendulum centre of mass (m)
$g=9.8$	Gravitational constant on Earth (m/s^2)
$\eta_m=0.69$	Motor efficiency
$\eta_g=0.9$	Gearbox efficiency
T	Torque on the load from the motor
$k_t=0.00767$	Motor torque constant (N m/A)
$k_g=19$	Total gear ratio
$k_m=0.00767$	Motor back-EMF constant (V s/rd)
$R_m=2.6$	Motor armature resistance (Ω)
V_m	Motor input voltage
θ	Rotating arm angle
α	Pendulum angle

$$T_{output}=\frac{\eta_m\eta_g k_t k_g(V_m-k_g k_m\dot{\theta})}{R_m} \quad (3)$$

$$\begin{bmatrix}\dot{\theta}\\ \dot{\alpha}\\ \ddot{\theta}\\ \ddot{\alpha}\end{bmatrix}=\begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & 33.30 & -16.73 & 0\\ 0 & 67.48 & -11.84 & 0\end{bmatrix}\begin{bmatrix}\theta\\ \alpha\\ \dot{\theta}\\ \dot{\alpha}\end{bmatrix}+\begin{bmatrix}0\\ 0\\ 29.43\\ 20.82\end{bmatrix}V_m \quad (4)$$

$$\begin{bmatrix}\theta\\ \alpha\end{bmatrix}=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\begin{bmatrix}\theta\\ \alpha\\ \dot{\theta}\\ \dot{\alpha}\end{bmatrix} \quad (5)$$

3. Mathematical model of the ball and beam system

The experimental setup of the ball and beam system is presented in Fig. 2.

The control goal is to govern the position of ball by applying a suitable voltage level to a servo motor. The ball can be maintained in steady state by adjusting an angle of the beam through the movement of the servo motor. The position of the ball is obtained