Expert Systems with Applications 41 (2014) 4274–4289

Contents lists available at ScienceDirect

Expert Systems with Applications

journal homepage: www.elsevier.com/locate/eswa

Performance analysis of fractional order fuzzy PID controllers applied to a robotic manipulator

Richa Sharma, K.P.S. Rana *, Vineet Kumar

Instrumentation and Control Engineering Division, Netaji Subhas Institute of Technology, Dwarka, New Delhi 110078, India

ARTICLE INFO

Keywords:
Two-link planar rigid robotic manipulator
Fuzzy logic controller
Fractional order fuzzy PID controller
Cuckoo search algorithm
Trajectory tracking
Robustness testing

ABSTRACT

A two-link robotic manipulator is a Multi-Input Multi-Output (MIMO), highly nonlinear and coupled system. Therefore, designing an efficient controller for this system is a challenging task for the control engineers. In this paper, the Fractional Order Fuzzy Proportional-Integral-Derivative (FOFPID) controller for a two-link planar rigid robotic manipulator for trajectory tracking problem is investigated. Robustness testing of FOFPID controller for model uncertainties, disturbance rejection and noise suppression is also investigated. To study the effectiveness of FOFPID controller, its performance is compared with other three controllers namely Fuzzy PID (FPID), Fractional Order PID (FOPID) and conventional PID. For tuning of parameters of all the controllers, Cuckoo Search Algorithm (CSA) optimization technique was used. Two performance indices namely Integral of Absolute Error (IAE) and Integral of Absolute Change in Controller Output (IACCO) having equal weightage for both the links are considered for minimization. Numerical simulation results clearly indicate the superiority of FOFPID controller over the other controllers for trajectory tracking, model uncertainties, disturbance rejection and noise suppression.

1. Introduction

For the past three decades, the use of robotic manipulators in industrial applications such as assembly, painting, pick and place, welding and accurate positioning etc. has extensively increased. For these applications, the control of end-effector of a robotic manipulator is a challenging task as it is a complex coupled system. The control of robotic manipulators has a long history and offers an open research area to the control engineers because of advancements in intelligent control techniques. Naturally, being simple in nature, conventional PID controller is the first choice for control engineers in industries. These controllers fail to provide an effective control to nonlinear, uncertain and coupled systems despite all their advantages (Reznik, Ghanayem, & Bourmistrov, 2003). The development of fuzzy controllers is a paradigm in the field of control engineering due to their nonlinear linguistic mapping between inputs and outputs. The capability and utility of conventional PID controller has increased to a good extent due to its hybridization with fuzzy logic controllers (FLC) (Wei, 1998). It provides a flexible and model-free approach to control engineers for designing a controller based on their own intuitions for the systems with uncertainties and nonlinearities (Lee, 1990; Ohtani & Yoshimura, 1996). Chen stated that the fuzzy logic based PID controller deals with linear, complex nonlinear, uncertain and higher order systems (Chen, 1996).

Different structures of fuzzy controllers for the linear as well as nonlinear systems have been investigated by several authors. Tang and Chen proposed an improved fuzzy PI controller for the flexible joint-robotic arm with uncertainties for the trajectory tracking control in which the FLC designed has three simple membership functions and six rules. The tracking performance of the proposed controller was as good as conventional PI. It was able to perform good tracking with uncertainties within 10% tolerance of nominal model parameters (Tang & Chen, 1994). Sooraksa and Chen proposed a fuzzy $(PI + D)^2$ scheme for trajectory tracking and vibration suppression applied to a shoulder-elbow-like flexible-link robotic manipulator. The stability of proposed controller was shown with a novel two-straight lines method. The proposed controller was claimed to be effective and robust for set-point tracking, disturbances and vibration suppression (Sooraksa & Chen, 1998). Er and Sun presented a new hybrid controller with fuzzy PI and conventional D in incremental form for the linear as well as nonlinear systems. The main feature of the proposed controller is that the conventional PI controller was replaced with fuzzy PI. Tuning of optimal gains was done with Genetic Algorithm (GA). The performance index chosen was weighted combination of rise time, percentage maximum overshoot, percentage steady-state error and percentage non-minimum. The proposed controller was superior

* Corresponding author. Tel.: +91 1125099050.
E-mail addresses: richasharma_7@yahoo.co.in (R. Sharma), kpsrana1@gmail.com (K.P.S. Rana), vineetkumar27@gmail.com (V. Kumar).

0957-4174/$ - see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.eswa.2013.12.030

to both conventional PID and some fuzzy PID controllers for temperature control system. The proposed controller was also worked effectively for a missile model. Also, the proposed controller was found to be robust against addition of white noise (Er & Sun, 2001). Li et al. designed a fuzzy P + ID controller for a robot manipulator and implemented on a direct-drive two-link manipulator. It was found that tuning of four parameters of proposed controller takes less time than the parameters of PID controller. The maximum deviation in tracking performance for the manipulator having mass at joint with proposed controller was 0.4707 and 0.2377 for joint 1 and joint 2 respectively. Similarly, the robot manipulator with mass at tip resulted in maximum deviation 0.5433 and 0.6116 for joint 1 and joint 2 respectively (Li, Chang, Wahl, & Farrell, 2001). Song et al. implemented a new hybrid control approach by combining traditional computed torque control (CTC) technique with fuzzy logic for the trajectory tracking problem of a two-link elbow planar robotic manipulator where fuzzy logic acted as compensator. The effectiveness of adding compensator in presence of uncertainties was presented with the help of simulation results. This paper interestingly provides thorough information about conventional CTC (Song, Yi, Zhao, & Li, 2005). Meza et al. presented a semiglobal asymptotic stability of new fuzzy self-tuning PID controller using Lyapunov theory for a robotic manipulator. The hardware implementation of the proposed controller was also done on a direct drive vertical robotic arm. The performance of proposed fuzzy self-tuning PID was better than conventional PID. This improvement in the tracking performance is due to the use of variable gain matrices (Meza, Santianez, Soto, & Llama, 2012).

Traditionally, the field of control theory has been dominated with integer order controllers. With the innovation in the field of fractional calculus, it was evident that fractional order integral and differential can be used in control applications to offer more flexible design of PID controller. In 1832, Abel applied the fractional order calculus for the equations of tautochrone problem. Since then, the fractional mathematics has entered into different fields like signal processing, system theory and feedback control etc. (Micharet, Chen, Jara, & Xue, 2010). In fractional order control design, conventional differentiator term 's' and integrator term '$1/s$' are replaced by 's^{μ}' and '$1/s^{\mu}$' respectively where 'μ' is the fractional order parameter.

The significant research in the field of FOPID controllers for different plants/processes has been cited by several authors. Petras presented a hardware implementation of digital FOPID control for a DC motor. The digital realization of proposed controller was done with the help of microprocessor and the analogue realization was done using fractance circuits. The method used for fractional implementation was based on Bode's ideal closed loop. This work presents the practical realization and implementation of fractional order controllers (Petras, 2009). Delavari et al. reported a fractional adaptive PID controller for robotic manipulator in which parameters of PID are updated online whereas other two fractional order parameters are determined offline. The tracking error presented graphically and was claimed to be less. The performance was enhanced with the proposed controller as compared to its integer order design (Delavari, Ghaderi, Ranjbar, HosseinNia, & Momani, 2010). Bingul and Karahan applied a FOPID controller to a robotic manipulator for trajectory tracking problem using Particle Swarm Optimization (PSO) and GA. The robustness testing of the proposed controllers was done for mass change, noise rejection and with different trajectories. The simulation results showed that FOPID controller using PSO was better than that tuned with GA. Also, PSO outperformed GA in terms of time taken to optimize and performance for searching the optimal solutions (Bingul & Karahan, 2012). Pan and Das designed a FOPID controller for automatic voltage regulator (AVR) using chaotic multi-objective optimization. The improved chaotic non-dominated sorting GA II (NSGA II) was used for optimization of parameters. It was concluded that FOPID controller is not completely better than conventional PID controller for all performance specifications. The simulation results were better for FOPID for some cases and for PID in the other cases. Also, it was reported that PID is preferred over FOPID if the cost is high in controller design (Pan & Das, 2012). Zamani et al. proposed a FOPID controller for AVR system using PSO. The performance index chosen was the combination of time domain and frequency domain specifications. The proposed controller was claimed to be more robust and effective than the conventional PID (Zamani, Ghartemani, Sadati, & Parniani, 2009). Tang et al. also investigated FOPID controllers for AVR systems using chaotic ant swarm (CAS). The CAS tuned FOPID outperformed other controllers namely GA-tuned FOPID, PSO-tuned FOPID, PSO-tuned PID and CAS-tuned PID. The proposed controller was robust to uncertainties in the amplifier, exciter and generator of the AVR model (Tang, Cui, Hua, Li, & Yang, 2012).

After the effective use of FOPID controller, the research trend has been towards the use of FLC with fractional order mathematics. Delavari et al. proposed fuzzy fractional surface sliding mode controllers for coupled tank system and robotic manipulator. The robustness testing was done with 20% variations in system parameters. The tuning of controller parameters was done with GA. The proposed fuzzy PD and PD^{α} sliding mode controllers were claimed to be superior to both PD and PD sliding surface controllers in terms of set point tracking performance and chattering (Delavari, Ghaderi, Ranjbar, & Momani, 2010). Das et al. presented the simulation results for FOFPID controller applied to delayed non-linear systems and open loop unstable process with time delay. The fractional order controllers were implemented with Oustaloup's approximation. The simulation results for FOFPID, FPID, FOPID, and PID controllers for the different performance indices were found to be contrasting in cases such as set-point tracking, load-disturbance and small control signal (Das, Pan, Das, & Gupta, 2012). Das et al. also presented a performance comparison study of different structures of FOFPID controller applied to oscillatory fractional order processes with dead time for set-point tracking, load disturbance rejection and control signal. The multiobjective NSGA-II was used to test the trade-offs between performance of set-point tracking and control, and set-point tracking and load disturbance. For the lag-dominant FO process, the FOF P + ID controller was best in case of tracking vs. small control and the FOF PD + I controller was best for tracking vs. load disturbance rejection. For the balanced lag and delay FO process, Both FOF P + ID and FOF PD + I were best in case of tracking vs. small control and FOF PI + D was best for tracking vs. load disturbance rejection. The FOF PID and FOF PD + I were best for tracking vs. small control and tracking vs. load disturbance for the delay dominant FO processes respectively (Das, Pan, & Das, 2013).

For the optimum performance, the tuning of parameters is an essential requirement for all conventional as well as intelligent controllers. With the advent in computational intelligence, various nature-inspired and evolutionary algorithms have evolved for optimization of different problems in the field of engineering. Several authors presented advanced optimization techniques such as GA (Bagis, 2007; Juang, Huang, & Liu, 2008; Wang & Kwok, 1994), Simulated Annealing (SA) (Davidson & Harel, 1996; Vasan & Raju, 2009), PSO (Gaing, 2004; Nasri, Pour, & Maghfoori, 2007), Ant Colony Optimization (ACO) (Chen, Guo, & Liu, 2009; Hai-bin, Dao-bo, & Xiu-fen, 2006), Tabu Search (Bagis, 2011; Puangdownreong & Sujitjorn, 2007), Firefly Algorithm (Yang, 2009), Artificial Bee