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Robust adaptive control of a bio-inspired robot manipulator using bat algorithm

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ABSTRACT

This paper proposes a novel adaptive fractional order PID sliding mode controller (AFOPIDSMC) using a Bat algorithm to control of a Caterpillar robot manipulator. A fractional order PID (FOPID) control is applied to improve both trajectory tracking and robustness. Sliding mode controller (SMC) is one of the control methods which provides high robustness and low tracking error. Using hybridization, a new combined control law is proposed for chattering reduction by means of FOPID controller and high trajectory tracking through using SMC. Then, an adaptive controller design motivated from the SMC is applied for updating FOPID parameters. A metaheuristic approach, the Bat search algorithm based on the echolocation behavior of bats is applied for optimal design of the Caterpillar robot in order to tune the parameter AFOPIDSMC controllers (BA-AFOPIDSMC). To study the effectiveness of Bat algorithm, its performance is compared with five other controllers such as PID, FOPID, SMC, AFOPIDSMC and PSO-AFOPIDSMC. The stability of the AFOPIDSMC controller is proved by Lyapunov theory. Numerical simulation results completely indicate the advantage of BA-AFOPIDSMC for trajectory tracking and chattering reduction.

1. Introduction

In the field of engineering, bio-inspiration (Hsu & Juang, 2013) can be investigated in mechanisms, designing and control significantly is modifying state of the art in robotics (Juang, Chen, & Jhan, 2015). Researchers investigate the measuring effects of animal locomotion in order to define the optimal gait for given-size robot. Limbless animals such as Caterpillars and Snakes are among the most accessible animals in each part of the Earth due to their structures and locomotion mechanisms. Their locomotion mechanisms are based on the flexible movements of their bodies. Investigating the Caterpillar locomotion in order to change it into a robot will be effective as an engineering application. According to Fig. 1, the movement of the Caterpillar could be categorized in different steps. First of all, the extending situation of the Caterpillar is considered as a primary status, then the endpoints contact with the ground. In the next step, the Caterpillar releases a wave, hence, its rear endpoint moves to grasp the ground. In the last step, the frontal section moves, and finally the Caterpillar in a further situation return to its initial position. This feature can be used in a robot in various fields such as inspecting gas pipes (Bodnicki & Kamiński, 2014; Wang, Song, Wang, Guo, & Tan, 2011; Yamashita et al., 2011; Zhou, Tao, Cheng, Liu, & Fu, 2013), using in medical issues (Zarrouk, Sharf, & Shoham, 2010, 2011, 2012; Zarrouk & Shoham, 2013). Ghanbari, Rostami, Noorani, and Fakhrabadi (2008), considering the inspiration of Caterpillar locomotion of the nature, proposed the model of the movements of the robot. They classified the locomotion mechanism into two sub-mechanisms. As a result, they demonstrate the snapshot of Caterpillar gait locomotion using Matlab program. As follows; the dynamic equations are obtained using Euler–Lagrange equations. And then, the trajectory tracking of joints has been optimized by Genetic Algorithm in order to minimize the consumed effort. A reduction of 5–37% in torque consumption has been obtained (Ghanbari & Noorani, 2011). Hopkins and Gupta (2014) designed a robot that was inspired from the snake. Regarding its hyper-redundant body, it can pass through tight spaces. This robot is faster than its previous structures that rectilinear gaits were used in them. The frictional force mainly occurs by high speed linear motion. The Worm robot has been built in different structures such as Nickel Titanium Coil Actuators (Kim et al., 2009; Seok et al., 2013) and Origami (Onal, Wood, & Rus, 2011, 2013).

PID controller is a convenient method in trajectory tracking that is acceptable for accurately implementing and tracking performances. The PID controller includes three independent parameters.

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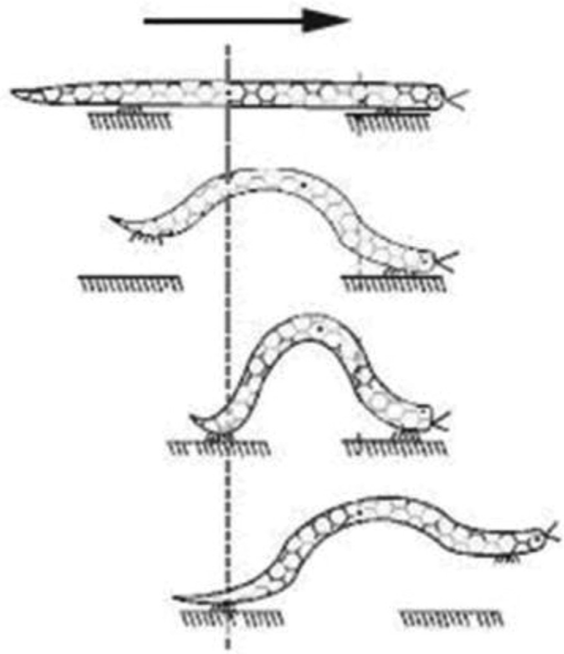

Fig. 1. Caterpillars locomotion (Juhász & Zelei, 2013).

By tuning the three parameters in the PID controller, the controller can provide control operation designed for particular developing demands. Ayala and dos Santos Coelho (2012) presented a multi-objective genetic algorithm for PID parameters' tuning applied to a robotic manipulator. The proposed NSGA-II optimization method provides an application process to implement a robust solution for trajectory tracking in closed loop. Different methods such as Neural Networks (Yu & Rosen, 2013), Fuzzy logic (Pan, Gao, Miao, & Cao, 2015), Fuzzy Neural Network (Wai & Muthusamy, 2014), etc., efficiently suggested tuning the parameters of PID controllers. In recent years, the fractional controller has been developed in Lan, Gu, Chen, Zhou, and Luo (2014), Muresan, Dulf, Copot, De Keyser, and Ionescu (2015), Tang, Zhang, Zhang, Zhao, and Guan (2013) and Vinagre, Monje, Calderón, and Suárez (2007). Podlubny (1999) proposed the fractional order PID controller as an extension of PID controller. It utilizes fractional order Integrals and derivatives and also it can supply robustness and obtains higher efficiency than the common integer controllers (Li, Luo, & Chen, 2010). The suggested method in Li et al. (2010) is based on frequency analysis and is considered for SIS systems. Dumlu and Erenturk (2014) observed that transient and steady-state error values have been reduced with the $PI^{\lambda}D^{\mu}$ controller for the Maryland manipulator tracking control in comparison to the conventional PID controller.

In most cases that PID controller has been used, the lack of high robustness and the average of trajectory tracking are mentioned. SMC gives us the best tracking performance. This method is very useful and popular because of its robustness in comparison to decompensation certainty in dynamic model. Different approaches have been carried out for improving trajectory tracking robot arms by using SMC, such as an adaptive sliding mode control (Soltanpour, Khooban, & Khalghani, 2016) and an expression of the sliding mode controller (SMC) for robot arms in generalized velocity components (GVC; Herman, 2005). Capisani and Ferrara (2012), while using SMC, have minimized the value of chattering. In some cases, the robot arms are in contact with the surface. The force of the contact surface that can be obtained by using a sensor is at the risk of damaging. Zeinali and Notash (2010) using SMC had reached to good trajectory tracking without using the sensor.

A Metaheuristic optimization algorithm can be utilized in order to tune the controller parameters in different engineering problems. Maldonado, Castillo, and Melin (2013) proposed the optimization of the type-2 membership functions for the average approximation of type-2 fuzzy controller using PSO. They compared the simulation results of the optimization using the PSO approach with genetic algorithm. Pedro, Dangor, Dahunsi, and Ali (2014) proposed a nonlinear control method utilizing dynamic neural network-based input-output feedback linearization for a quarter-car active vehicle suspension systems. They optimized the gains of the proposed controllers and the weights of the dynamic neural network using PSO. Hashim, El-Ferik, and Abido (2015) proposed a novel practical method based on fuzzy rules for online tuning L_1 adaptive controller parameters. They reduced both the tracking error and the controller input signal range with fuzzy controller, which is optimally tuned using PSO. Therefore, we can apply PSO in different engineering problems as an effective optimization algorithm (Li & Wu, 2011; Tavakkoli-Moghaddam, Azarkish, & Sadeghnejad-Barkousaraie, 2011; Zhu, Wang, Wang & Chen, 2011). BA is completely stronger than PSO, genetic algorithm and Harmony Search (Yang, 2011). The mainly reason is that BA uses an appropriate combination of significant advantages of mentioned algorithms. Abd-Ekazim and Ali (2016) proposed for optimal tuning of PI controllers for load frequency controller design. The numerical simulation results demonstrated the superiority of BA in comparing with Simulated Annealing in PI controller optimization. A PID cascade controller applied to the control of an interconnected, multi area thermal system. Controller parameters are tuned at the same time using powerful evolutionary computational approach BA (Dash, Saikia, & Sinha, 2015). Osaba, Yang, Oiaz, Lopez-Garcia and Carballedo (2016) proposed a discrete version of the BA to solve the famous Travelling Salesman problems. Furthermore, they presented a development in the fundamental structure of the classic BA. The experimental results have demonstrated that the proposed developed BA outperforms completely all the other alternatives in most of the problems. So, BA can be considered as a powerful optimization tool (Meng, Gao, Liu & Zhang, 2015; Svecko & Kusic, 2015).

SMC has some good advantages such as acceptable tracking performance, resistance to disturbances and its disadvantages are poor stability and chattering. Because of the vast benefits of the FOPID controller, the main problem of this controller can be stated as its low tracking performances. In this paper, a new robust adaptive control has been proposed, in which it is suggested that control system is able to eliminate their disadvantages, of FOPID controller and a new robust adaptive control, to control a Caterpillar robot manipulator. An adaptive controller design is motivated from the sliding mode control and is applied for updating FOPID parameters. In the following, Bat algorithm optimization was used to design and select the control parameter using an optimal approach. The stability of the proposed control system can be guaranteed considering the Lyapunov stability theorem. The performance of the suggested control system has been compared with classical PID, SMC, FOPID, AFOPIDSMC and PSO-AFOPIDSMC. The simulation results have been shown that the performance of proposed controller can be considered as the best in comparison to the others.

The rest of this paper was organized as follows. In Section 2, the summary was explaining the motion of the robot. In Section 3, obtaining dynamic equations was defined through utilizing the Euler–Lagrange equation. Section 4 included the sliding mode controller. In Section 5, the fractional-order PID controller was described. Section 6 defined adaptive robust fractional-order PID sliding mode controller. The implementation of fractional-order