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Hybrid control of a parallel platform based on pneumatic artificial muscles combining sliding mode controller and adaptive fuzzy CMAC

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ABSTRACT

A three degree of freedom parallel platform based on pneumatic artificial muscle (TDOFPPM) with obvious features of nonlinearity, uncertainty and coupling is introduced in this paper. It would be a challenge to control a nonlinear system with strong uncertainties. The complexity of air flow and the hysteresis of pneumatic artificial muscle are the main uncertainties in the TDOFPPM system. A hybrid controller combining sliding mode controller and adaptive fuzzy CMAC (AFCMAC) uncertainty compensator has been proposed for TDOFPPM. In order to guarantee the approximation ability for those main uncertainties, the input space and parallel structure are carefully designed for AFCMAC compensator. Finally a TDOFPPM experiment facility is introduced and the posture tracking control of TDOFPPM under two reference input signals are presented. The experiment results indicate the performance of hybrid controller is favorable.

1. Introduction

There are more or less nonlinear phenomena in actual physical systems. Actually nonlinear systems are common, and linear system is only a special case among them (Khalil, 2002). There are always some uncertainties in nonlinear systems. It would be a challenge to control a nonlinear system with strong uncertainties. Generally there are two uncertainties which are from outside and from inside of the system. Various disturbance and measurement error are typical of the former. And unmodeled dynamics are typical of the latter. A parallel platform based on pneumatic artificial muscles (PAMs) is introduced in this paper, as shown in Fig. 1, which is a three degree of freedom (DOF) electromechanical system driven by three PAMs. The parallel platform was designed for waist rehabilitation training leveraging PAM's multiple unique advantages including simple structure, high power density, and similar elastic characteristics to biological skeletal muscles, and so on. These features make the parallel platform structure simple, and in the meantime make control process more compliant than traditional actuator method. In order to meet the requirement of rehabilitation training a certain control precision is necessary. However PAM is a pneumatic actuator with strong nonlinearity and uncertainty (Chou & Hannaford, 1996; Shen & Shi, 2011a,b). The three DOF parallel platform based on pneumatic artificial muscle (TDOFPPM) has obvious features of nonlinearity and coupling. On the other hand, because of the complexity of air flow and the hysteresis of PAM unmodeled dynamic is another primary character of TDOFPPM. All these characters make it very difficult to achieve good control performance, and even lead to instability.

Compared with linear systems, the study of nonlinear control systems is imperfect. Many approaches for nonlinear systems are introduced including feedback linearization, sliding mode control, backstepping, nonlinear $H\infty$ control, intelligent control and so on. Sliding mode control has been applied to nonlinear systems with strong uncertainty (Qian, Liu & Yi, 2009; Guo, Su, Liu & Liu, 2010). However chattering phenomenon, an inherent property of sliding mode strategy due to discontinuous switching, may create unmodeled high-frequency and even drive system to instability.

In 1980s, differential geometry was introduced into control theory, which greatly promotes the development of nonlinear control. The feedback linearization method based on differential geometry theory is an exact global linearization method. In this method some nonlinear state space equations could be transformed into linear equations so that some mature and powerful linear control theory could be used for nonlinear control (Isidori, 1995). Being the most theoretically rigorous method, feedback linearization consists of finding a feedback control law and a state variable transformation (diffeomorphism). By diffeomorphism the close-loop system model becomes linear in the new coordinate system. There has been considerable development in the study of feedback linearization of discrete-time systems (Grizzle & Kokotovic, 1998; Nam, 1989), as well as of continuous-time

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systems (Isidori, 1995; Marino & Tomei, 1995). Moreover, feedback linearization approach has been applied successfully to electromagnetic suspension system (Joo & Seo, 1997), pneumatic system (Kimura, Hara, Fujita & Kagawa, 1997; Xiang & Wikander, 2004), hydraulic system (Chiriboga, Thein & Misawa, 1995), robot (Vandegrift, Lewis & Zhu, 1994), spacecraft (Bang, Myung & Tahk, 2002), and so on.

However the feedback linearization method based on differential geometry theory demands accurate mathematical model of controlled system. As to many nonlinear systems with strong uncertainty accurate mathematical modeling of such systems is entirely impossible. In the result feedback linearization method often leads to great linearization error and thus reduces control performance, even causes instability. In order to overcome these drawbacks, some researchers (Yesildirek & Lewis, 1995; Lu, Shieh, Chen & Coleman, 2006; Floares, 2006; Hourfar & Salahshoor, 2009) studied artificial neural network (ANN) based feedback linearization method. In these methods ANN is utilized to model the whole nonlinear system with uncertainty or the difficult-to-model part of the nonlinear system.

As one of the artificial intelligent technologies that firstly emerged, ANNs have presented superb learning, adaptive, classification and function approximation properties. These advantages make their application in online system identification and close loop control. CMAC (Celebellar Model Articulation Controller) (Albus, 1975) represents an auto-associate memory feed forward neural network model firstly raised by Albus in 1970s. CMAC can be used for control learning, implementing a mapping or function approximation. The advantages of using CMAC over conventional ANN in many applications are well known in some literatures (Lane, Handelman & Gelfand, 1992). Conventional CMAC could not be used well in control of nonlinear systems with strong uncertainties for its week adaptive and convergence ability. In order to remedy such a drawback, fuzzy CMAC was proposed (Chiang & Lin, 1996; Geng & McCullough, 1997).

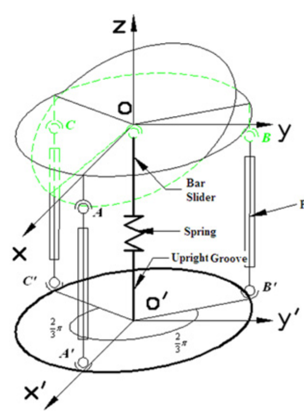

Fig. 1. The principle structure of TDOFPPM.

Manipulators actuated by PAMs have been studied by several researchers recently. (Chang, Liou & Chen, 2011) proposed a Takagi–Sugeno(T–S) fuzzy model-based control to improve control performance of a PAM joint manipulator. A nonlinear PID controller mixing conventional PID controller and ANN is introduced in (Thanh & Ahn, 2006) to control a practical 2 axes PAM manipulator. In (Choi & Lee, 2010) a novel method is suggested through the addition of an independent joint compliance controller to the position controller so that a two-link PAM manipulator's position and compliance can be controlled simultaneously. Zhu, Tao, Yao and Cao (2008) adopted a discontinuous projection-based adaptive robust control strategy to compensate for various uncertainties of a three DOF parallel manipulator to achieve precise posture trajectory tracking control. The three DOF parallel manipulator in Zhu, Tao, Yao and Cao (2008) is different from TDOFPPM in principle structure. And generally various uncertainties including hysteresis are not analyzed and settled seriously in above literatures.

This paper uses a hybrid controller combining sliding mode controller and adaptive fuzzy CMAC (AFCMAC) uncertainty compensator to control the TDOFPPM. Firstly the dynamic mathematical model of TDOFPPM is raised and linearized into three linear and independent subsystems by feedback linearization method. Then the sliding mode controller with approaching law is designed for each linear subsystem, and the uncertainties in every linearized subsystem are approximated by a set of adaptive fuzzy CMAC and compensated into an item in every control input.

Fig. 2. PAM of Festo Co.