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Position control of SMA actuator based on inverse empirical model and SMC-RBF compensation

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ABSTRACT

Due to the nonlinear saturated hysteretic behavior of SMA during the phase transformation, it is not easy to achieve accurate position tracking control by establishing an effective controller for the SMA actuator system. In this paper, an accurate position control method based on inverse empirical hysteresis model with simple structure and SMC-RBF compensation is proposed. The inverse empirical hysteresis model which shows the hysteresis effect of SMA wire for both heating and cooling processes is used to calculate a proper input voltage according to the desired position. Then, a compensation control part based on SMC-RBF is added to the closed-loop control system to estimate the difference between empirical hysteresis model and exact hysteresis effect, unknown dynamics, as well as disturbances, which can also minimize the requirement for an accurate inverse hysteresis model. Since the major part of input voltage for SMA actuator is calculated from inverse empirical hysteresis model, the proposed method shows faster response speed than the case in which only SMC-RBF is used. In addition, the position tracking results demonstrate that the proposed method has better tracking capability for trajectory with high frequency as well as less overshoot/undershoot than PID controller. Consequently, this proposed method with simple structure should be a viable alternative for position control of SMA actuators.

1. Introduction

Shape memory alloys (SMA) are metallic alloys which deform at low temperatures and return to the original un-deformed state when heated to higher temperatures. The shape memory effect is a consequence of a reversion in the crystalline structure between the low temperature and high temperature phases, which are respectively called the martensite and the austenite of the SMA. The martensite phase is non-symmetric and relatively soft, while the austenite phase is symmetric and relatively hard. Already, SMA have been used in a variety of actuation applications because of advantages such as excellent power-to-mass ratios, reliability, and silent actuation. These applications include mobile robots [1], micro-robot manipulations [2], smart structures [3], and artificial muscles [4]. However, the ability of SMA actuators to memorize a specific shape is the result of physical changes which occur in a highly nonlinear fashion, introducing significant hysteresis in the actuator response and making it difficult to model and control [5–7].

To control the tracking position of SMA actuators, the most conventional methods are PID controllers [8]. Ma et al. presented PD controller modulated by pulse width modulation (PWM) to reduce the energy consumption of the SMA actuator

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[9]. Shameli et al. developed a nonlinear controller PID-P^3 by combining PID with the cubic error to reduce the overshoot of SMA actuator [10]. Kwan Ahn et al. applied a self-tuning fuzzy PID controller which integrates fuzzy inference and produces a fuzzy adaptive PID controller, improving the control performance of nonlinear systems [11]. Jun et al. presented a fuzzy pulse-width-modulated controller that is capable of realizing co-contraction of SMA muscle pairs, as well as online tuning of the PID gains necessary to deal with parameter uncertainties [12]. However, these control methods mentioned above usually lead to large overshoot or undershoot caused by the hysteresis effect arising from the nonlinearities of SMA actuators, especially for square waveform trajectory [13].

To reduce the hysteresis problem of SMA actuators in the position control, several methods based on device design are developed. Selden et al. presented an approach to design and control of SMA actuators by using a Peltier model which can reduce the latency times of both the heating and cooling processes [14]. Tabrizi et al. provided a control scheme for angular position control of a rotary load using SMA wires in antagonistic configuration, which demonstrates fast and accurate position responses [15]. Lan et al. improved the position tracking accuracy of SMA actuator by adding a sufficient pretension force to achieve very small hysteresis gaps [16]. Zhang et al. proposed a forced vessel cooling method to improve the response speed of artificial muscle (actuated by SMA), which can satisfy the initial ankle–foot rehabilitation application [17]. Li et al. presented a rapid position tracking control method based on two connected SMA wires [18]. However, even though these kinds of improvements for devices can reduce the hysteresis effect of SMA actuators, these methods still either increase the weight of experiment or fail to obtain accurate tracking results.

To increase the position tracking accuracy and robustness of SMA, many hysteresis model-free schemes have been developed. Tai et al. implemented artificial neural networks (ANN) combined with a hysteresis operator to compensate the SMA hysteresis phenomenon [19]. Son et al. proposed neural networks (NN) method to approximate the unknown the hysteresis, which can reduce the position tracking error [20]. Sliding mode control (SMC) is a technique derived from variable structure control (VSC) which was studied originally by Utkin [21]. Among all kinds of variable structure control methods, SMC shows great robustness of stability and insensitivity to the variation of plant parameters and external disturbances. Therefore, SMC is a suitable choice for robot control system actuated by SMA or DC motors [22–24]. Kolyvas et al. proposed a control method based on SMC and spatial hysteresis approximation to remove the negative effects in nonlinear systems of SMA actuator [25]. In addition, the hybrid control strategies by combining SMC and NN [26], or SMC and time delay estimation (TDE) [27,28] are proposed as well recently, resulting in highly accurate and robust tracking control performance.

The radial basis function (RBF) neural network is one of the most widely used models in nonlinear control systems, which shows simpler structures, faster training speed and stronger generalization ability compared with other kinds of neural networks [29–31]. A hybrid control strategy by combining SMC and RBF (SMC-RBF) is developed to control the position of SMA actuator, which shows better position tracking performance than SMC [32]. In this paper, experiments are conducted to test the effectiveness of the control strategy SMC-RBF firstly. And the results will be compared with conventional PID, where the areas needed to be improved will be identified. Furthermore, a precise tracking control method based on the estimated inverse hysteresis model is proposed, using the SMC-RBF to compensate inverse hysteresis model and unknown dynamics of SMA actuator. The rest of this paper is organized as follows. The control method and experimental results based on SMC-RBF are investigated in Sections 2 and 3, respectively. Section 4 demonstrates the control scheme of the proposed method and Section 5 shows the experimental results. Finally, conclusions are made in Section 6.

2. Method based on SMC-RBF

As mentioned in many literatures, the dynamics of SMA actuated system can be expressed in a form of a nonlinear second-order system, which can be described as follows [33,34]:

$$J\ddot{x} + b\dot{x} + kx + d = f(x, \dot{x}, u) + \omega u \tag{1}$$

where $\ddot{x}$, $\dot{x}$ and x represent the acceleration, velocity and position of the system, respectively; J, b, and k denote an effective inertia, an effective damping, and an effective stiffness, respectively; d expresses unexpected disturbances; $f(x, \dot{x}, u)$ is the hysteretic nonlinear term; u is the input (applied voltage in this paper); ω is the input coefficient.

This second-order system shown in Eq. (1) can be expressed as:

$$u = [J\ddot{x} + b\dot{x} + kx + d - f(x, \dot{x}, u)]/\omega \tag{2}$$

Since RBF neural network (consisted by three inner layers: an input layer, a hidden layer with a non-linear RBF activation function and a linear output layer) has excellent approximation ability for nonlinear systems, it can be used to approximate the nonlinear dynamic system. Then, Eq. (2) can be rewritten as:

$$u = u_{RBF} \tag{3}$$

where $u_{RBF} = [J\ddot{x} + b\dot{x} + kx + d - f(x, \dot{x}, u)]/\omega$ is the output of RBF neural network, and it can also be given as [35,36]:

$$\begin{cases} u_{RBF}(k) = \boldsymbol{W^T}(\boldsymbol{k})\boldsymbol{H}(\boldsymbol{k}) \\ \boldsymbol{W^T}(\boldsymbol{k}) = [w_1(k), w_2(k), w_3(k), \cdots, w_n(k)] \\ \boldsymbol{H}(\boldsymbol{k}) = [h_1(k), h_2(k), h_3(k), \cdots, h_n(k)]^T \end{cases} \tag{4}$$