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Sliding mode-based control of thin Shape Memory Alloy actuators using a spatial hysteresis approximation☆

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ABSTRACT

Shape Memory Alloy (SMA) actuators rely their operation on a thermally driven phase change. The SMA's stroke position control problem thus involves the material temperature in a direct or indirect way. In thin SMA actuators, deviations between the actual and the estimation of the temperature profile can affect the performance of model-based control. In this work, an intermediary strategy, between a model-free and a model-based one, is proposed, where local approximations to the hysteretic trajectories are used in place of a complete hysteresis description. The localized trajectory is then spatially shifted to encapsulate the hysteretic behavior. A sliding mode based controller is constructed by this implementation exhibiting accurate tracking behavior. The advantages against existing model-free controllers are further investigated over a multi-rate control scheme. The results show that efficient tracking position control can be reached even at very low output feedback frequencies.

1. Introduction

Shape Memory Alloys (SMAs) have been used in a widespread variety of applications with a projected growth of use in the following years [1]. These applications range from aerospace [2] and morphing structures [3] to the automotive industry [4], the medical sector [5], and miniature robots [6], demonstrating their ability to operate under different environmental conditions and operation related specifications.

Factors, as actuator positioning accuracy, speed of operation or space limitations, usually determine the selection of sensors and the control approach. The change in the value of resistance is considered in [7] for position control of a medical device, while in [8] the inductance of a SMA-spring is used to estimate the actuator length. Ho et al. in [9] have used the combination of Magnetic Resonance Imaging (MRI) and material resistance as feedback for the control of an active endoscope during surgery. The use of MRI for feedback is reportedly slow for control purposes (~ 5 Hz) and has been complemented by the, fast sampled, electrical resistance.

The dependency on fast feedback loops, usually required for model-free control, can be relaxed, when accurate mathematical models are available. Physics based models are able to describe complex material phenomena such as creeping, rate-dependency effects and other inherent non-linearities [10]. However, their use requires additive effort in terms of parameter tuning and heuristic algorithms for model-inversion [11]. Phenomenological models (Preisach, Prandtl–Ishlinski and Krasnosel'skii-Pokrovskii) are more general mathematical descriptions of hysteresis and rely on a weighted collection of elementary functions [12]. They have been effectively used in model-inversion compensation schemes [13], but may be difficult to implement for control purposes when direct access to the material temperature is infeasible.

The requirement to have access to the accurate temperature profile can be restrictive and infeasible when considering high-rate excitation in non-controlled environments [14]. Changes in the environmental conditions can affect the heat transfer properties and cause deviations between the material temperature and the estimation. Uncertainties in the temperature profile have led to the use of a Bayesian framework for the bounding of the model uncertainty in [15], prior to the development of a robust controller. The problem of inaccurate static models has been identified in [16] and tackled by the use of a dynamic neural network. The parameters governing the convergence properties of the adaptation law and the activation functions create an additional parameter-tuning burden and require an internal optimization process for their selection.

In [17] a retrospective adaptive control has been suggested, based on an inversion-free adaptive method for SMA control. Since it relies on the notion that the control signal is refined based on the performance of previous control effort, it is best suited for

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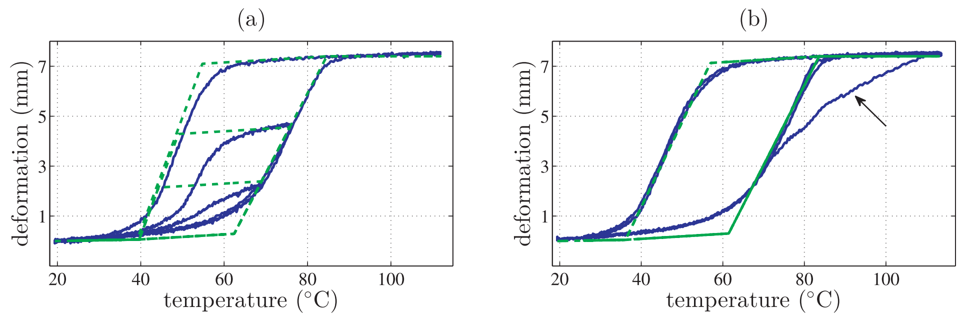

Fig. 1. (a) Piecewise linear approximation of the hysteresis trajectories (left) and (b) system – model mismatch due to change in the environmental conditions (right); Model trajectories appear in green-dashed and blue-solid lines are used for the experimentally obtained hysteresis curves.

periodic reference signals. Examination of the properties of the generalized play operator in [18,19] led to the proposition of robust controllers, based on the limits (boundedness) of the nonlinearity. The simulation results presented show high efficiency of the proposed scheme. The use of global bounds, similar to the method of employing global approximates (in [20]), although efficient can be conservative in terms of describing the uncertainty.

Piecewise approximations of the actuator dynamics have also been proposed to complement classic control schemes, as in [21]. The Time Delay Estimation (TDE) method has been used in [22, 23] with a PID in the first and a Sliding Mode Controller (SMC) in the second and has been enhanced in [24] to provide improved convergence characteristics. These methods are shown to exhibit high tracking performance and have generally low parameter tuning effort and are, for this reason, used here for benchmarking.

Previous works have also concentrated on the use of a relatively simple material model for control purposes. SMC on the basis of the Liang-Rogers model has been proposed in [25] for a general class of SMA actuators. Assuming access only to the output, an extended Kalman filter has been used to estimate the remaining states. The experimental results are accurate in terms of tracking performance, but it is reported therein that modeling inaccuracies and erroneous state estimation may affect the overall performance. Using a similar method, the dynamic response of an SMA actuator is examined in [26]. Nevertheless, even the use of this simple phenomenological model can lead to complicated expressions in the controller equation. An abstraction of this model is proposed in the following, for control purposes.

2. Need for adaptive characteristics in SMA modeling

Elementary operators like the relay or the play (backlash) describe basic characteristics of hysteresis [12]. A modification of the play operator is used in the following for the purpose of demonstrating that simple models can be efficient in describing the essential characteristics. Such static descriptions though, can be inaccurate if variations (disturbances) in the state variables are not directly accessible/ measurable. The effects of this inability are demonstrated in Fig. 1. This requirement, to update the system description by using current data, as opposed to static information given by phenomenological models, is central in the proposition of this work.

A piecewise linear approximation (in the sense of [27]) of the recorded hysteresis trajectories in the input-temperature (θ) and output- deformation (ϵ) at the time instant i is given in Fig. 1(a) by use of Eq. (1). This static approximation is based on the play operator, examined in its elementary and generalized form in [28] and used as part of a generalized Prandtl–Ishlinskii model in [29]. The rationale in the making of Eq. (1) is further discussed in Appendix A. In systems where the temperature sensing is not available though, as in thin-wire actuators under fast dynamic excitation, the presence of anomalies in the temperature profile, can lead to significant system-model mismatch. This phenomenon is demonstrated by the arrow in Fig. 1(b), where a wind-draft causes instant drop in the material temperature and momentarily suspends the transformation.

$$\epsilon_i = \min\left\{E^h_\circ(\theta_i - A_f), \max\left\{E^l_\circ(\theta_i - \theta_\infty), \max\left\{E_a(\theta_i - A_s), \min\left\{E_m(\theta_i - M_f), \epsilon_{i-1} + \Theta(\theta_i - \theta_{i-1})\right\}\right\}\right\}\right\} \quad (1)$$

Variations of the heat transfer characteristics due to the change from natural to forced convection have been the subject of investigation under [13]. A hybrid Model Reference Adaptive Controller (MRAC) supported by a PI-controller has been used therein for the position tracking of the SMA-actuator. The scope of this hybrid scheme has been to actively adjust the temperature dynamics according to a reference model via the MRAC.

3. Hysteresis mitigation strategies in the controller design of piezo and SMA actuators

The availability of direct access to the controlling parameters of hysteresis (state variables), operating specifications of the actuator (frequency range, environmental conditions), availability and bandwidth of feedback sensors are some of the considerations that guide the selection of the control strategy. Similar hysteretic phenomena are inherent in smart materials, but the role of hysteresis in the control loop can be different when coupled with the associated actuator dynamics. Table 1 summarizes some key characteristics of hysteresis and control considerations for piezo and SMA driven actuators. Piezoelectric transducers are used for the comparison, given their wide implementation in actuators with high commercial value. This comparison is performed to describe the context for the proposition in this work.

The operation of piezos over a wide frequency range creates control challenges, like vibrational resonance, that may have a stronger impact on the actuator operation than hysteresis effects. The control design problem then may focus on specific actuator characteristics (as in [36]). Contrary, the operation of SMA actuators is generally restricted at a bandwidth lower than 1 Hz (depending also on the exact actuator-geometry), determined by the low heat transfer coefficient for natural convection [3,38]. Even at this low frequency operating regime, the presence of uncertainty in the value of the state variables, makes the use of closed-loop methods preferential in real applications.

Table 2 provides a short comparison of general control strategies and their limitations when applied to piezo and SMA applications respectively.[1] Similarities are also identifiable in some control strategies, among different types of smart actuators, when

[1] The methods identified intend to provide a brief outline of some of the available techniques and are not an exhaustive survey on the subject.