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Modeling a shape memory alloy actuator using an evolvable recursive black-box and hybrid heuristic algorithms inspired based on the annual migration of salmons in nature

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ABSTRACT

The purpose of current investigation is to engage two efficient evolvable neuro-evolutionary machines to identify a nonlinear dynamic model for a shape memory alloy (SMA) actuator. SMA materials are kind of smart materials capable of compensating any undergo plastic deformations and return to their memorized shape. This fascinating trait gives them versatility to be applied on different engineering applications such as smart actuators and sensors. As a result, modeling and analyzing of their response is an essential task to researchers. Nevertheless, these materials have intricate behaviors that incorporate the modeling with major dilemma and obstacles. In this research, two novel evolvable machines comprised recurrent neural network (RNN) and two novel hybrid heuristic methods nominally cellular automate and Kohonen map assisted versions of The Great Salmon Run (CTGSR and KTGSR respectively) optimization algorithm are developed to find a robust, representative and reliable recursive identification framework capable of modeling the proposed SMA actuator. To elaborate on the acceptable performance of proposed systems, several experimental tests are carried out. Obtained results reveal the promising potential of the evolvable frameworks for modeling the behavior of SMA as a complex real world engineering system. Furthermore, by executing some comparative tests, the authors indicate that both of their proposed hybrid heuristic algorithms outperform the sole version of TGSR as well as some other well-known evolutionary algorithms.

1. Introduction

Shape memory alloys (SMAs) are a class of smart materials that can compensate the induced plastic deformations and return to their original shape by different stimulus such as: thermal energy, electrical forces, magnetic forces, ultraviolet light, pH, and chemical energy. Having this behavior which is called shape memory effect (SME) enables these materials to contribute in many applications such as micro-actuation [1], aerospace [2], medical industry [3], vibration damping [4], robotics [5] and automotive [6]. Specifically, the SMA actuators can produce relatively large displacements and have a high force/weight ratio with respect to traditional actuators. Moreover, they offer the following advantages: simple design, smooth motion, easy miniaturization, bio-compatibility, noiseless operation, simplicity of actuation and low power consumption [7]. Accompanying these unique characteristics, its industrial applications are limited due to slow response speed and their inherent nonlinear behavior that makes them difficult to be controlled. However, the nuisances produced by these intrinsic weaknesses can be kept to a minimum using a precise model of the actuator and a robust and reliable controller. The efficiency of an SMA actuator depends on the performance of its controller, which in turn depends on the mathematical model of the SMA.

Over the past couple of decades, a vast amount of researches have been carried out on modeling SMA actuators, particularly in capturing their hysteresis properties. Arai et al. [8] developed a nonlinear differential equation to detect the behavior of SMA actuators by fitting the proposed model to experimental data. Since the proposed model was not based on the actual physical governing equations, its performance cannot be guaranteed over the entire operating region. Liang and Rogers [9] proposed a nonlinear constitutive model that includes the hysteretic behavior. The proposed model includes many parameters that should be determined experimentally. Recently, Elahinia and Ahmadian [10,11] presented improved models of previous works supported by experimental studies. The Preisach model has also been used to model the hysteresis of the SMA [10]. Although this model explains the

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hysteresis characteristic and the minor loops, the formulation is based on experimental data and not on the actual process. This model is also not convenient for developing control strategies. All the proposed models include many parameters with a wide range for their values. These parameters are not constant and vary for different materials and working conditions. Therefore it is unavoidable to identify their values for each applications and usages using the related experimental data.

Due to the complexity of the actuator behavior and the hard nonlinearity of the model structure, the identification algorithm is very important. Hence, adaptive identification and control of hysteresis in smart materials, including SMA, is an ongoing research. Soft computing is an interdisciplinary concept which comes to the aid of engineers in variety of applications such as complex system management [12], control [13], intelligent manufacturing [14], robotics [15,16], bio-mechanics [17], pattern recognition [18] and engineering optimization [19]. In recent years, regarding to these versatility and immense number of promising reports in literatures, researchers have switched to the application of soft and intelligent computational methods to model both nonlinear and hysteric behaviors of engineering systems instead of implementing tedious mathematical models. The main provocations for this eagerness can be regarded in two main aspects. Firstly, the appeal of designing a self-imposed dynamic model (black box identifier) unrelated to the knowledge of any expert user. Secondly, the appeal of developing a robust identification model with acceptable generalization capability. Although the dynamic black box identification systems have several advantages, their performance and accuracy strictly relate to the training strategy. Devising an efficient training methodology is the most important step in designing a nonlinear artificial identification system. Up to now, several deterministic and stochastic algorithmic methods have been proposed to provide an efficient training approach that guarantees the maximum generalization of dynamic identification models. Luitel and Venayagamoorthy [20] proposed a quantum inspired particle swarm optimization (PSO-QI) for training a multi input multi output (MIMO) recurrent neural network (RNN). They observed that RNN can effectively learn MIMO systems when trained using PSO-QI. Xu et al. [21] investigated the performance of particle swarm optimization (PSO), differential evolutionary (DE) and hybrid of DE and PSO (DEPSO) to train RNNs for modeling the nonlinear dynamics of genetic networks. Cai et al. [22] proposed a hybrid swarm/evolutionary metaheuristic to train the RNN for predicting the chaotic time series. Juang and Chang [23] developed an elite-guided continuous ant colony optimization (ECACO) for designing a recurrent TSK fuzzy model.

In the case of SMA modeling, Tai and Ahn [24] fused the PSO algorithm with a hysteric functional link artificial neural network (HFLANN) for both identification and model predictive control of SMA actuator. They indicated that their method can provide a powerful controller capable of compensating the SMA hysteresis phenomenon. Ma et al. [25] developed a neural network to control the position of shape memory alloy actuators with internal electricity resistance. Song et al. [26] utilized a sliding mode robust controller and neural network for dynamic position tracking control of shape memory alloys. They developed an inverse neuro model to compensate the SMA hysteric phenomena. Pirge et al. [27] utilized a hybrid neuro genetic strategy as an inverse identification system to find the composition of any NiMnGa alloy. In their work, genetic algorithm (GA) was just used to find the optimum synaptic weights of neural network. Asua et al. [28] developed a neural network controller capable of positioning a SMA actuator. Ahn and Kha [29] proposed an internal model control for shape memory alloy actuators using extreme input history and a fuzzy based Preisach model.

In spite of the widespread researches for modeling the dynamic behavior of SMAs, there exist rare reports addressing the use of incremental/inductive learning approaches and evolving computation (EC) based strategies for modeling SMA's hysteric behavior. It has been proved that EC can highly ascend the generalization and interpretability of any identification model [30–32,72,73]. In the light of such superiorities, scientific communication engaged the concept of EC to tackle several theoretical and practical obstacles [74], e.g. the effect of multi-level adaption in EC, potential of EC for handling non-stationary environments, application of EC for tuning the self-organizing maps (SOMs), EC in real-time robot control, EC for training neuro-fuzzy systems and etc. Along with the application of EC to neuro computing tasks, it has also proved its aptitude in the field of fuzzy computing. A seminal work by Lughofer endorses on the authenticity of different EC based algorithms and methodologies for adapting the characteristics of the fuzzy systems [75]. The realm of applications of EC has also been expanded to evolving a wide spectrum of intelligent systems. In [76], a rationale is provided which address some useful EC methodologies for different informatics and engineering applications. EC has proved its eligibility for learning in dynamic environments as well. This issue is fully discussed in a seminal book by Sayed-Mouchaweh and Lughofer [77]. Application of EC in online learning of expert systems is a relatively recent spotlighted concern which attracts the attention of numerous researchers [78]. The motivation behind the current investigation emanates in the pursuit of addressing the efficacy of EC in online adaption of intelligent systems. The main concepts behind designing any evolving identifier can be focused from four different angles that are mentioned in below:

(1) Incrementality of the learning methods to devise any real time identifier.
(2) Online adjusting of both architecture and constructive parameters of identifier systems.
(3) By using an evolvable dynamic identification system, the computational complexity decreases significantly since it is not needed to re-train the black box identifier after each data updating process.
(4) An efficient evolvable framework provides some useful information about the optimum topology and accuracy of identification system.

The main contribution of the current research can be divided into two parts. Firstly, given all abovementioned remarks, authors intend to examine the potential of EC for modeling the hysteric behavior of SMA actuator in a real time manner. Secondly, they engage the EC concept to design an intelligent tool (evolving black box identifier) capable of modeling the hysteric behavior of SMAs without having any information about the governing equations and physical conditions. The developed intelligent tool comprised RNN (a common recursive black box) and two hybrid natural inspired supervisors called CTGSR and KTGSR (heuristic methods which evolve both topology and parameters of the black box). Experiments prove that by embedding both cellular automate (CA) concept and Kohonen map (SOM) within the structure of TGSR [33], the computational complexity does not vary significantly while both speed and accuracy of evolving process rise significantly.

The rest of the paper is organized as follows. Section 2 describes the structure of the SMA actuator. The identification black box (RNN) is discussed in Section 3. Section 4 is devoted to the details of both CTGSR and KTGSR evolving techniques. Moreover, some well-known dynamic benchmark problems are used to test the performance of proposed methods. The experimental setup for obtaining the necessary identification data is presented in Section