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Position control of SMA actuators with internal electrical resistance feedback

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ABSTRACT

This paper presents the development of a position control system for a shape memory alloy (SMA) wire actuator using the electrical resistance feedback. It is commonly known that an SMA actuator is highly nonlinear and a position sensor is often required to achieve a stable and accurate positioning. And this position sensor often contributes a large portion of the system cost. To eliminate the position sensor in an SMA actuator system, a novel control theme is proposed by utilizing the actuator's electrical resistance feedback. With an SMA wire test setup, the relationship between the electrical resistance and the displacement is experimentally investigated. However, this relationship is highly nonlinear, and a neural network is employed to model this relationship and predicts the position of the actuator using only its electrical resistance information. To enable feedback control of the SMA wire actuator using only its electrical resistance, a Proportional-Integral-derivative (PID) controller is used. Feedback control experiments are performed and the results demonstrate that the proposed position control system achieves a good control performance without using a position sensor.

Keywords: Shape memory alloy, position control, electrical resistance feedback, hysteresis, neural network modeling.

1. INTRODUCTION

Shape memory alloy (SMA) has been receiving increasing attentions in recent years due to its unique ability to return to a predetermined shape when heated. This property is caused by the reversible crystalline phase transformation between its low temperature martensite to its high temperature austenite.

Austenite and martensite are two SMA phases having the same chemical composition and atomic order, but different crystallographic structures. Austenite owns a body centered symmetric structure and exists at high temperature, while martensite has a low symmetric monoclinic structure and stabilizes at relatively low temperature. When it is cooled from high temperature, SMA undergoes the martensitic transformation from the high-temperature austenite to the low-temperature martensite. Because the bound energy between the martensite layers is low, the martensite can be easily deformed. Even after removal of the stress, the strain remains. The residual strain can be recovered by heating the material to the austenite phase and SMA returns to its original shape (called the shape memory effect).

During the martensite-austenite transformation, SMA exhibits a large force against external resistances. A 0.02-inch diameter nickel-titanium alloy (NiTi) wire can lift as much as 16 pounds, associated with 5% length recovery. This property enables SMA to be a potential actuator in many fields. In recent years, the investigations of employing the SMA actuators in the micro-robot manipulation, aircraft wing shape control and micro-system precise control have been conducted. In these cases, precise regulation of the actuator is desired. However, the hysteresis associating the transformation makes it a challenge to accurately control the SMA actuator.

In the literature, two categories of the control algorithms have been used for the position control of the SMA actuator. The first kind of the algorithm is to compensate or reduce the hysteresis effect by incorporating a reverse dynamic model of the SMA actuator into the control system. There are several models of the SMA actuator. For example, Ikuta *et al.* [2] proposed a variable sub-layer model of SMA in 1991, and Brinson *et al.* [1] developed a one-dimensional constitutive model relating the stress to the state variables of the strain, temperature and martensitic fraction. However, these models may not be practical since many model parameters have to be experimentally determined.

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The second kind of the control algorithm relies on a feedback control loop that is capable to stabilize the SMA actuator and improve the actuation performance. The position, temperature, or electrical resistance (ER) of the SMA actuator can be used as the feedback signal in the control system. Among these state variables, the position is the most widely used as the feedback signal. Song [6] proposed a sliding-mode based robust control system for an SMA wire actuator. A Linear Variable Differential Transformer (LVDT) is used to feedback the SMA position. The experiments show that the control system with the position feedback can accurately control the position of the SMA actuator. However, the essential position sensor dramatically raises the system's cost and size. Feedback control with the temperature feedback has been also investigated recently. The researches demonstrate that the temperature feedback control is not practical because it is difficult to precisely measure the likely disturbed temperature of the SMA actuator in an open environment.

On the other side, the relationship between the ER variation and strain of an SMA actuator during the transformation is deterministic and repeatable to some extents. The reason is that the variation of ER is determined by the martensite fraction (the transformation degree) and the strain, and under a certain stress condition, the strain is a function of only the martensite fraction. This property inspires utilizing the ER as a measurement of the strain or the displacement to control the SMA position without a position sensor.

In 1988, Ikuta *et al*. [3] developed an antagonistic SMA actuator system for an active endoscope. Based on their experimental result that the force generated by the antagonistic SMA actuator has a nearly linear relationship with the normalized electrical resistance, they designed a force control system with the ER feedback for the real size active endoscope. However, their conclusion may not be correct for a spring-biased SMA actuator (For this type SMA actuator, the return force is provided by a bias spring), because in comparison with the latter, the antagonistic SMA actuator has a small temperature hysteresis. In fact, many researches [4,5,7] have shown that the ER variation during the transformation is complex and sensitive to both temperature and stress. Therefore, it is desirable to investigate the ER variation for the spring-biased SMA actuator.

Recently, Raparelli *et al.* [5] reported an electrical feedback control system for a constantly loaded SMA actuator system. Since the return force is provided by a constant weight, the stress on the SMA actuator is fixed during the transformation. They observed a small hysteresis in the curves of the strain vs. ER and they used a linear function to approximate the curves, neglecting the hysteresis. Because the ER change is indirectly affected by the stress on the SMA actuator, obviously their work neither solves the problem of position control of a spring-biased SMA actuator using the electrical resistance feedback.

The following sections will present our research to develop a position control system for a spring-biased NiTi wire actuator using the electrical resistance feedback. First, an experimental setup, which is used for the purposes of both the preliminary tests and the control system implementation, will be introduced. Then, the ER variation of the NiTi wire was investigated through the preliminary experiments under different activation conditions. A neural network was employed to approximate the relationship between the displacement and the ER. Based on the neural network model, a Proportional Integral and Derivative (PID) position control system of the NiTi wire actuator using its electric resistance feedback was developed and successfully tested.

2. EXPERIMENTAL SETUP

The experimental setup is illustrated schematically in Figure 1. This setup includes three major sections: a testing platform, a PC-hosted real-time control system and a programmable power supply.

The testing platform (as shown in Figure 2) is designed for testing and control of a single NiTi wire. The wire is 228.6 mm in length, 0.381 mm in diameter and is characterized with a 90 degree F austenite-finish temperature. The fixed end of the wire is connected to the platform frame and the moving end is attached to a steel cable. The steel cable is linked to a linear-bearing supported slider through two pulleys. The slider can only move horizontally, as constrained by the linear-bearing. A tension spring is used to pre-tension the SMA wire. In addition, an LVDT, whose tip is against the slider, is used to measure the displacement of the slider. It is clear that the motion of the slider is controlled by the deformation of the SMA wire actuator. The pretension can be adjusted by changing the equilibrium position of the slider at low temperature. When the NiTi wire is electrically heated and experiences a phase transformation to the stronger austenite, the wire will contract and move the slider. Once the electric current is removed, the wire cools and it will transform to its weak martensite phase. The tension spring will pull the wire back to its cold length.

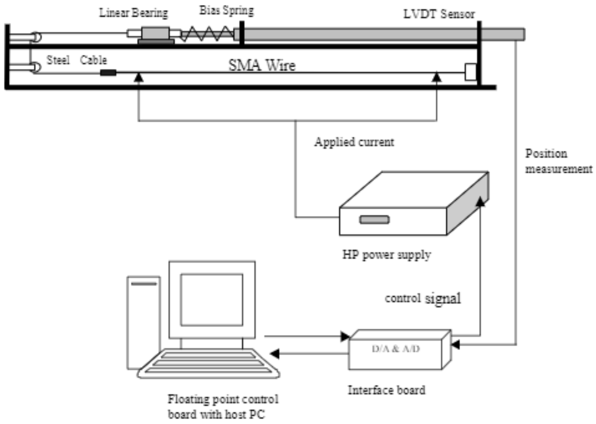


Figure 1 The experimental setup.

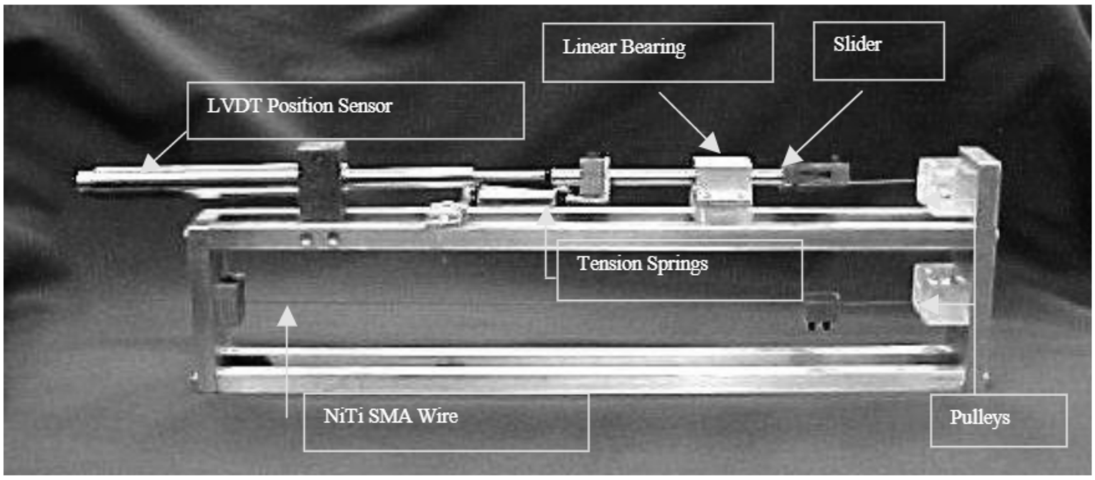


Figure 2 The experimental setup: the platform.

3. PRELIMINARY TESTING ON THE NITI WIRE ACTUATOR

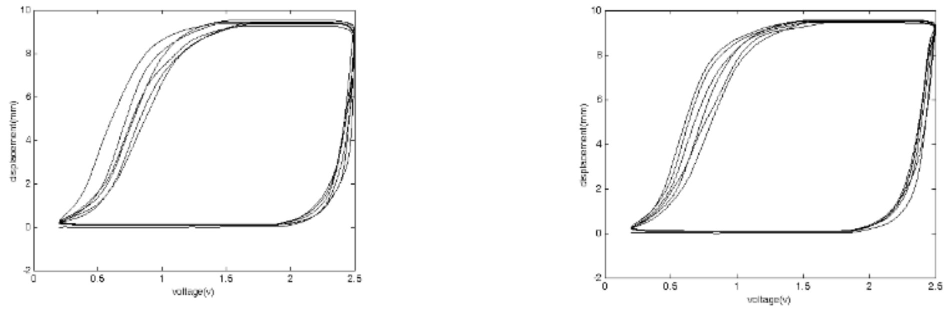
In the first step, a series of experiments have been conducted to investigate the relationship between its electric resistance (ER) and the displacement of the NiTi wire. The necessities of these tests are as follows. First, although there are many researches on the SMA's ER variation from the perspective of the material science, the results cannot be used in this paper since they studied the SMA actuator under either a constant temperature or a constant stress condition, which will not hold in most real applications of an SMA actuator, especially for our case, where the SMA wire that is subject to a varying stress during the thermal-induced transformation. Few published works addressed the SMA's ER variation in such a case. Second, since the ER variation is complex and sensitive to many factors such as the heat treatment, the chemical components and the transformation path, it is necessary to test the each kind of the SMA actuator with a ER feedback control.

To explore the ER-displacement relationship of the spring-biased NiTi wire actuator, open-loop tests are conducted first. In the test, a sine-wave voltage signal is used to activate the NiTi wire actuator. The input frequency is as slow as 1/60 Hz to ensure a full phase transformation of the SMA wire actuator.

The tests were conducted under different activation conditions such as with different pre-tensions, different maximum stresses and different magnitudes of the input voltages in order to study the effects of these conditions on the ER variation. The experiments and results are presented as following.

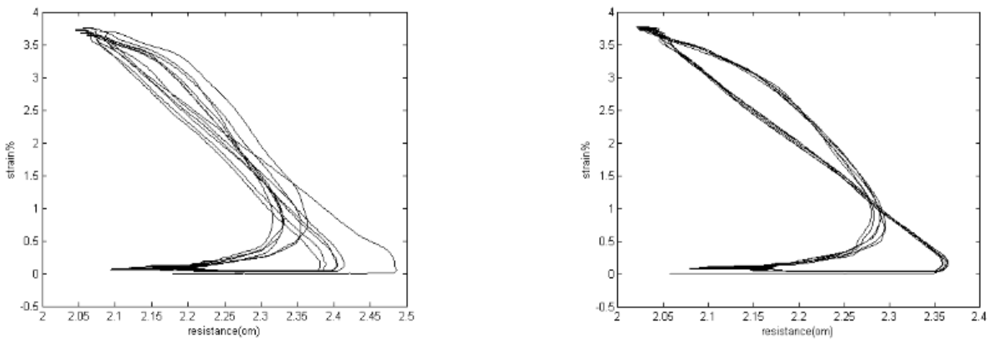
In the first set of experiments, the NiTi wire was electrically heated by the 1/60 Hz sine-wave voltage signal. The pre-tension on the wire is fixed. During the experiment, it was found that the ER-displacement curves do not overlap at the beginning stage of the experiment. Hence, two sets of the data were collected at different time intervals. The experimental results are shown in Figures 3 and 4.

There are two noticeable phenomena. First, the hysteresis is observed in the relationship of the ER and strain. In Figure 4, it is obvious that the ER values (corresponding to a same strain value) are different in the heating and cooling processes and the slope of the curve varies in each activation cycle. When the wire is heated, before the transformation takes place, the curve is horizontal (the slope is zero) and the ER decreases at a nearly constant rate (the slope is negative) after the wire contracts. However, the ER behaves differently in the cooling process. At the beginning of the martensitic transformation, the ER increases at a large rate, and as the transformation advances, the increasing rate becomes smaller until the ER decreases (The slope of the curve continuously varies from a negative value to a positive value). The ER hysteresis is caused by the difference between the austenite-Rphase-martensite transformation in cooling and the direct martensite-austenite transformation in heating [4]. R-phase has a crystallographic structure similar to that of the martensite and has a large resistance value. Under some conditions in a cooling process, the parent phase (austenite) is transformed to R-phase and then R-phase is transformed to the martensite phase. Therefore, the ER value in cooling is larger than that in heating at the beginning of the transformation. There is competition between the austenite-martensite transformation and the austenite-R-phase transformation. As its temperature becomes cooler, the R-phase is transformed to the martensite. That is the reason why the ER decreases at the end of the cooling process.



(a) (b)

Figure 3 Displacement vs. applied voltage in the first test: (a) the first set of data and (b) the second set of data.



(a) (b)

Figure 4 Strain vs. ER in the first test: (a) the first set of data and (b) the second set of data.

The second phenomenon is that the hysteresis is not stable at the beginning stage of the experiment. Figure 4 shows the strain vs. ER curves at different time. Figure 4(a) corresponds to the data recorded in the first 360s of the test, while

Figure 4(b) exhibits the ER variation after 900s activation (15 activation cycles). It is obvious that the curve repeats itself well after being activated for some time. The explanation for this phenomenon is that the residual strain gradually decreases to zero after some activation cycles [7].

The second sets of tests were conducted under the different maximum stresses on the wire. The maximum stress on the wire can be set up by adjusting the pre-tension on the wire as long as the wire moves the same distance. The results are shown in Figures 5 and 6. It is noticeable that the large stress reduces the ER hysteresis width. Under the large stress condition, the R-phase is almost skipped and the austenite is directly transformed into the martensite [7, 8]. Moreover, the large pre-tension decreases the range of the ER change and increases the ER value for the same strain in comparison with the case of small pre-tension.

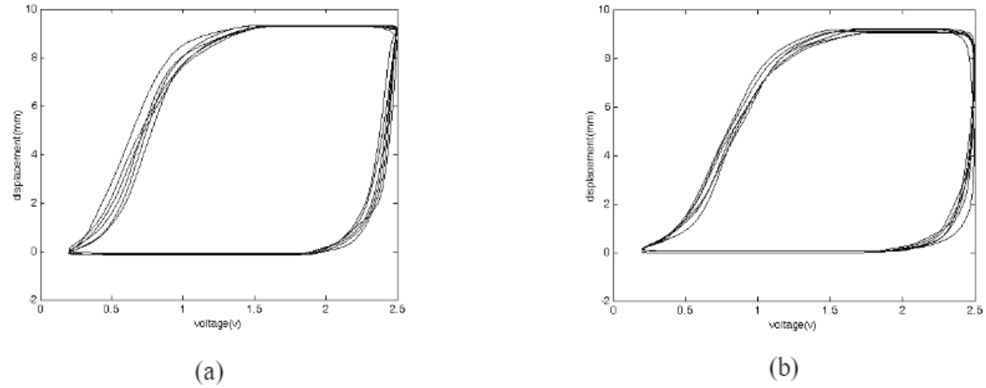


Figure 5 Displacement vs. applied voltage in the second test: (a) under small pretension and (b) under large pretension.

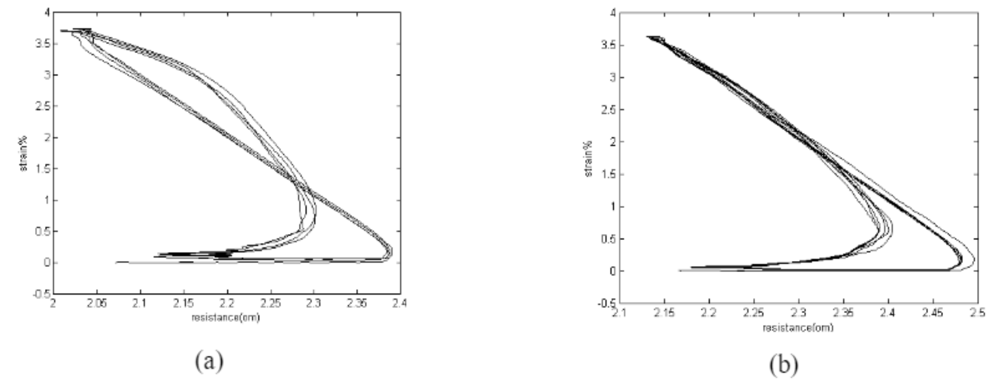


Figure 6 Strain vs. ER in the second test: (a) under small pretension and (b) under large pretension.

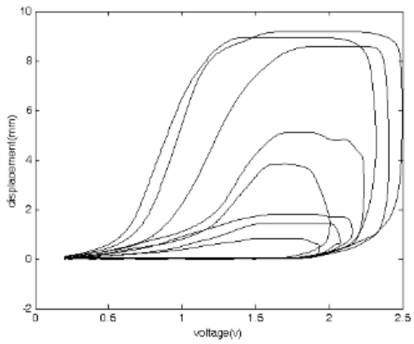


Figure 7 Displacement vs. applied voltage.

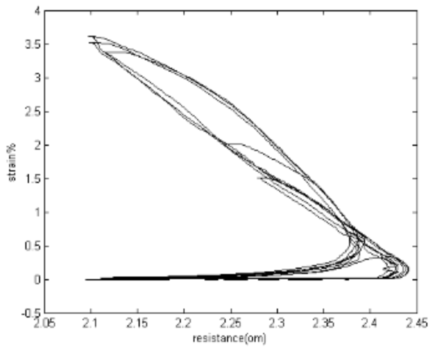
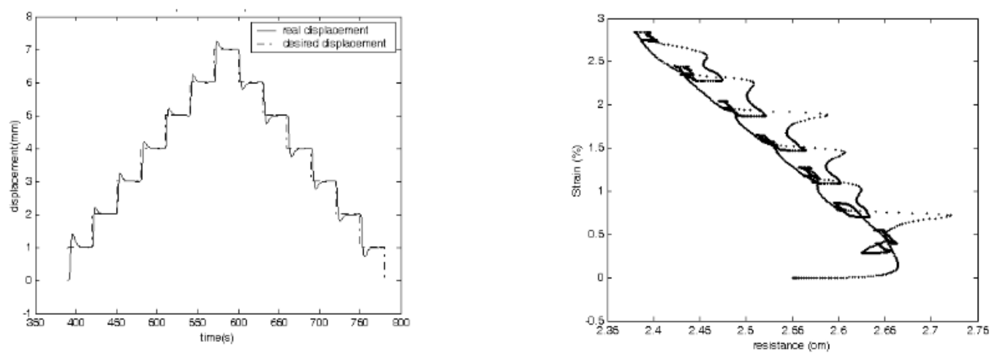


Figure 8 Strain vs. ER in the third test.



(a)

(b)

Figure 9 The results of the closed-loop preliminary test: (a) system response and (b) strain vs. ER.

Different from the above two sets of tests in which the transformations are fully completed in each cycle, the third test was designed to explore the ER variation during the uncompleted transformation using a decaying sine-wave voltage signal. The magnitude of the applied voltage gradually decreases from 2.5 V to 1.9 V in 360s. In Figures 7 and 8, it is clear that the minor hysteresis loops corresponding to the uncompleted transformations are enclosed by the major loop and the minor loops eventually converge to the major loop as the actuating voltage increases.

The shortcoming of the above open-loop tests is that the ER variation between two positions is not illustrated clearly. Thus, a closed-loop preliminary test was conducted in the paper. The closed-loop test uses a PID position controller. A multi-step command is input and the PID controller ensures that the slider is at the desired position for each step input. In Figure 9(a), the steady state error is less 0.002mm for each step input. It is interesting that the curves shown in Figure 9(b) have very similar characteristics. The same trend has been observed in the major loops shown in Figures 4, 6 and 8.

4. MODELING OF THE ER HYSTERESIS USING NEURAL NETWORK AND POSITION CONTROL DESIGN

It is evident from the last section that the ER-strain relationship is hysteretic, and the relationship is not fully repeatable and complex in the minor loops. There is about 15% variation of the displacement in the stable major loop. However, the displacement or position of the SMA wire can still be estimated from the measured ER to some extents. For the modeling purpose, one major hysteresis loop (shown in Figure 10) is selected to represent the ER behavior in the stable state. For some applications of the SMA wire actuator, the error induced by the choice of the representative loop is acceptable.

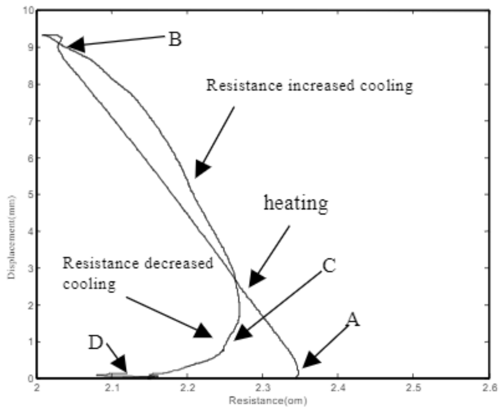


Figure 10 The representative hysteresis loop for the neural network training.

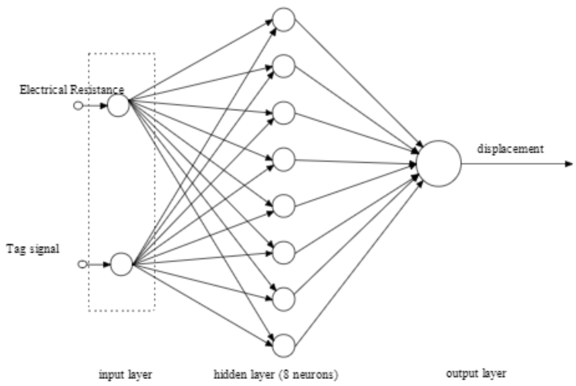


Figure 11 The structure of the neural network.

A multilayer neural network is designed to model the relationship between the ER and displacement of the representative loop. The multilayer neural network has a three-layer structure (shown in Figure 11), with one hidden layer having 8 neurons. The two inputs are the ER and a "tag" signal. Due to the hysteresis, the displacement vs. ER curve is not one-to-one, i.e. one ER value corresponds to two or three displacement values. Therefore, the "tag" signal is used to distinguish the different segments of the representative loop based on the slope change. The representative loop is divided into three segments: AB, BC and CD. The AB segment has a negative slope and corresponds to the heating process. The BC has a negative slope and represents the resistance increase in cooling. In the same cooling process, the CD segment however has a positive slope.

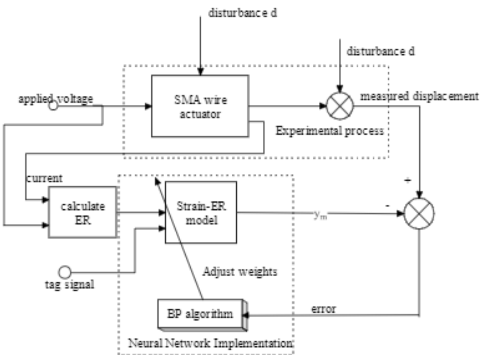


Figure 12 The schematic of training the neural network.

The training of the neural network is illustrated in Figure 12. Data from the representative loop are used to train the neural network until its output fits the real output well. The simulation result of the trained neural network and the real displacement of the NiTi wire actuator are shown in Figure 13. It is evident that the neural network accurately approximates the displacement as a function of the ER.

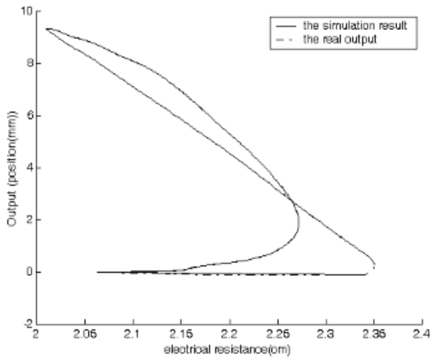


Figure 13 Comparison of the simulation result and the real output

A closed-loop position control system for the NiTi wire actuator was designed and implemented in this paper. In the block diagram of the control system (Figure 14), the ER is computed using the applied voltage and the measured current on the NiTi wire. The trained neural network model estimates the displacement of the NiTi wire from the given ER value. The error signal, the difference between the desired position and the predicted position, is fed to a PID controller. The control signal is amplified using a programmable power amplifier and then applied to the wire to drive the SAM actuator. The LVDT sensor is used to measure the position of the slider for the purpose of verification.

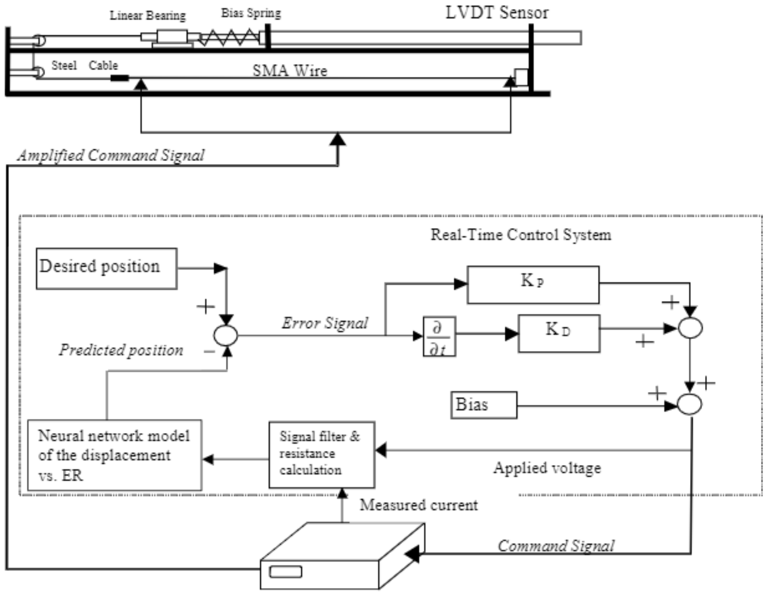


Figure 14 The block diagram of the control system.

5. EXPERIMENTAL RESULTS AND DISCUSSION

The experiment was carried out to test the proposed position control system of the NiTi wire actuator. In the experiment, a multi-step position signal is sent to the control system. Each position command lasts for 30s and the difference of the positions is 1mm. The desired displacement ranges from the 1mm to 7mm. Figure 15 shows the controlled position responses in the experiment. The average position error is about 7% in the steady state and it is clear that control accuracy as the NiTi wire is heated is much better than that as the wire is cooled. Although the position control accuracy of the ER feedback control is relatively larger than that of the position feedback control, the performance is still good and acceptable for some applications, considering that there is no position sensor used and there is an error induced by the choice of the representative major loop.

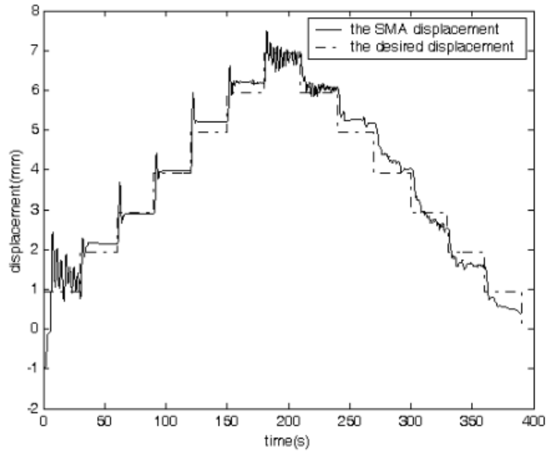


Figure 15 The SMA actuator's response

6. CONCLUSIONS

In this paper, the electrical resistance (ER) feedback control system of the spring-biased NiTi wire actuator is proposed. Through the preliminary tests on the actuator, it is observed that the ER-strain relationship is hysteretic and shows the complicated behavior under the effects of several activation conditions. It is demonstrated that a multilayer neural network has the ability to model the major ER hysteresis loop and to predict the displacement using the ER value for the feedback control purpose. A PID position control system based on the neural network model is designed and implemented on the experimental setup. The experiment on the control system illustrates the ER feedback control is feasible and can be acceptable in some applications.

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