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Active position control of a shape memory alloy wire actuated composite beam

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Abstract. This paper presents the design and the experimental result of the active position control of a shape memory alloy (SMA) wire actuated composite beam. The composite beam has a honeycomb structure with SMA wires embedded in one of its face sheets for the active actuation. The potential applications of this experiment include thermo-distortion compensation for precision space structure, stern shape control for submarines, and flap shape control for aeronautical applications. SMA wires are chosen as the actuating elements due to their high recovery stress (>500 MPa) and tolerance to high strain (up to 6%). However, SMA wires are inherently nonlinear and pose a challenge for control design. A robust controller is designed and implemented to actively control the tip position of the composite beam. The experiment set-up consists of the composite beam with embedded SMA wires, a programmable current/voltage amplifier to actuate the SMA wires, an infrared laser range sensor to detect the beam tip displacement, and a real-time data acquisition and control system. The experimental result demonstrates the effectiveness of the robust control.

(Some figures in this article are in colour only in the electronic version; see www.iop.org)

1. Introduction

Shape memory alloys (SMAs) are materials which have the ability to return to a predetermined shape when heated. An SMA object can experience a reversible crystalline phase transformation, which enables the SMA object to recover its original heat-treated shape (up to 6% strain) when heated above a critical transformation temperature or to generate high recovery stresses (>500 MPa is possible). SMAs are often used as actuators (Ito *et al* 1995, Mukherjee *et al* 1996). SMA actuators have many potential applications, such as active shape control of space antenna reflectors, vibration reduction for rotorcraft with active flap control, and active deicing systems for fixed-wing aircraft, among others. As compared with piezoelectric actuators, SMA actuators have the advantages of being able to generate either larger deformations or forces. SMA can also be fabricated into different shapes. Among them, SMA wires are often used (Shu *et al* 1997, Taylor *et al* 1998). SMA wires can also be embedded into the face sheet of the structure of interest, such as a helicopter blade, and actively alter the shape of a structure in a desired fashion.

The unique properties of SMAs result from a phase transformation in their crystal structure when cooled from the stronger, high-temperature form (austenite) to the weaker, low-temperature form (martensite). The alloy undergoes a martensitic transformation of a type that allows the alloy to be

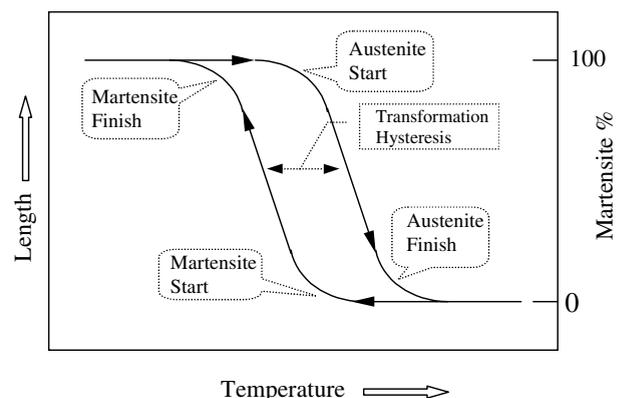


Figure 1. Transformation hysteresis against temperature for a SMA actuator under constant load (stress) as it is cooled and heated.

deformed by a twinning mechanism below the transformation temperature. The deformation is then reversed when the twinned structure reverts upon heating to the parent phase.

The transformation exhibits a hysteretic effect, in that the transformations on heating and on cooling do not overlap (figure 1). Thus SMA actuators exhibit hysteresis, a nonlinearity, which adversely affects precision control of the structures activated by SMA actuators. To design control methods to compensate for the nonlinearity associated with SMA actu-

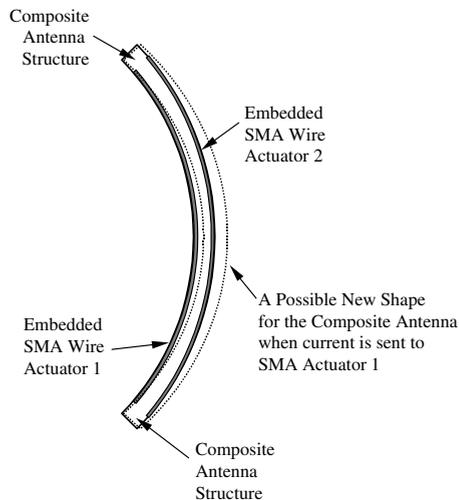


Figure 2. A smart space antenna with active shape control using embedded SMA wire actuators.

ators poses a challenge for control engineers and researchers. Conventional linear control designs cannot solve this problem alone, and this motivates the use of advance control methods.

In this paper, a new approach employing a robust controller is developed for tip position control of a composite beam with embedded SMA wire actuators. These wire actuators are embedded within a low modulus elastomeric face sheet attached to a honeycomb core. The composite beam can be deformed by supplying direct current ranging from 1.5–3.0 A to the SMA wires, and the tip of beam can move up to 1.5 cm if the base-end is fixed. Based on previous work with proportional and derivative control (Song *et al* 2000), a new approach employing a robust compensator is used to compensate for the nonlinearity associated with this composite beam. A real-time code is developed and implemented to control the tip position of the composite beam with the base-end fixed. The experimental result demonstrates the effectiveness of the robust control approach.

2. Experimental set-up

2.1. Motivation and potential applications

New spacecraft applications, including space-based lasers and space-based radar are being designed with stringent structural requirements for pointing accuracy. As space structures become larger and pointing accuracy becomes higher, the need for precision active shape control becomes increasingly important. In addition, thermal distortion for precision space structures must be compensated. To meet these challenges, ‘smart structures’ employing SMA actuators are being researched.

Figure 2 shows a smart composite space antenna with active shape control using SMA wire actuators. SMA wire actuators are embedded into both surfaces of the composite antenna. Due to adverse effects, such as thermal distortion, the surface shape of the antenna may deviate from its desired shape. To correct this error, a calculated current is sent to the appropriate SMA wire actuator to ensure that the antenna shape returns to the desired shape. To be able to precisely

control the SMA wire actuator, and therefore the shape of the antenna, is a key step towards the implementation of a smart composite space antenna.

Another possible aerospace related application of SMA actuators is rotorcraft vibration reduction. Rotorcraft vibration reduction has been a challenging task since the inception of rotorcraft. One of the most promising new methods for vibration reduction in helicopters is the actively controlled trailing edge flap. Using this approach a partial span trailing edge flap located on the outboard region of the blade is used to modify the unsteady aerodynamic loading along the span of the blade in a manner that minimizes vibratory loads (figure 3). To be able to precisely control the trailing edge flap position is the central idea to reduce rotorcraft vibration due to aerodynamic loading.

2.2. A composite beam with embedded SMA wire actuator

By keeping the aforementioned potential applications of SMA actuators in mind, a composite beam with embedded SMA wire actuators was developed, as shown in figure 4. When heated, the SMA wire actuators can deform the composite structure. For simplicity, SMA wire actuators are only embedded into one side of the composite beam. A composite beam is used because of its light weight and the convenience to embed actuators. SMA wires are chosen as actuating elements due to their high recovery stress (>500 MPa) and tolerance to high strain (up to 6%).

The overall dimensions of the beam are 30.48 cm long, 5.08 cm wide, and 1.32 cm thick. Figure 5 provides a top view of the beam. Figure 6 presents a side view of the beam. The beam is constructed from a 1.27 cm thick 5052 aluminium honeycomb core, with a 0.81 mm thick glass fibre reinforced polymer composite backbone, a 2.54 mm thick Conathane[®] urethane casting polymer compliant face sheet, and two polymer termination blocks. SMA wires are embedded within a low-modulus elastomeric face sheet attached to honeycomb core. The opposing side of the beam consists of a high-modulus glass epoxy bonded to the honeycomb core. The elasticity of the beam provides the restoring force. There are 16 0.381 mm diameter, 30.48 cm long, nickel–titanium SMA wires (two sets of eight wires electrically wired in parallel) embedded in the compliant face sheet. The corresponding circuit resistance of the wires is 10.3 Ω (Kelly 1998).

The SMA composite beam can be activated by supplying a current ranging from 1.5 to 3.0 A to the SMA wires. The exact amount of current depends on the desired response time and the degree of actuation. Currents in excess of 3 A or extended hold times at maximum deflection can result in degradation of the urethane face sheet.

2.3. Overall experimental set-up

The purpose of the experiment is to actively control the tip motion of the composite beam actuated by the SMA wire actuators. A photograph of the overall composite beam experiment is shown in figure 7. The major components of this experiment include an Hewlett–Packard

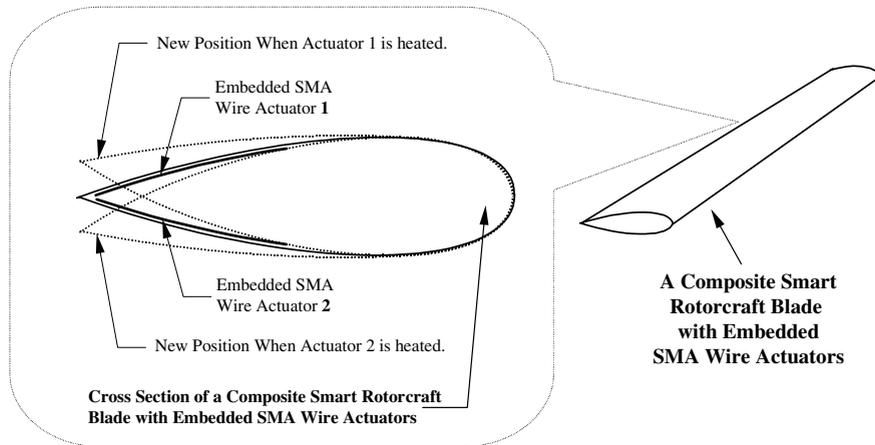


Figure 3. Vibration reduction in rotorcraft using actively controlled trailing edge flaps.

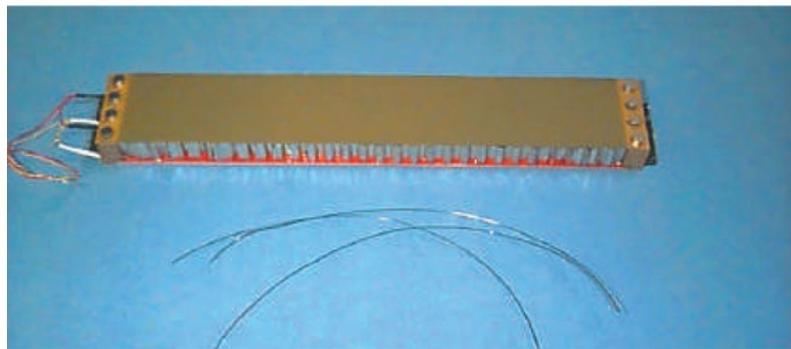


Figure 4. Photograph of the composite beam with embedded SMA wire actuators and some SMA wires.

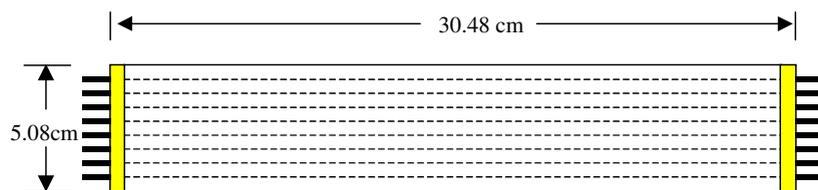


Figure 5. Schematic diagram of a SMA composite beam (top view).

(HP) programmable power supply (model 6542A), an HP low-voltage power supply, the composite beam, an NAIS laser analogue sensor (model LM100), an HP oscilloscope, a PC (not shown in figure 7) loaded with Matlab/Simulink, and a dSPACE data acquisition and real-time control system (also not shown in figure 7). The dSPACE system employs a Texas Instruments C-30 digital signal processor (DSP).

As shown in figure 7, one end of the composite beam is fixed to the supporting structure and the other end can move once the embedded SMA wires are supplied with current. The NAIS laser analogue sensor (model LM100) is used in this experiment to detect beam tip displacement. The measurable range of the laser sensor is 80–180 mm, and it has an output voltage range from -5 to $+5 V_{dc}$. This output signal is then sent to the dSPACE digital data acquisition system for feedback control.

A real-time control design environment with MATLAB/Simulink and dSPACE interface software is used to design controllers and to generate real-time codes. The real-

time code is then downloaded to the DSP for real-time control. The control signal from the dSPACE system is amplified by the HP programmable power supply (model 6542A) and then sent to the SMA wire actuator to activate the composite beam. The power supply has a range of 0–20 V or 0–10 A and can be programmed to operate in either a voltage-control mode or a current-control mode.

In the voltage-control mode, the power supply output voltage is proportional to an input voltage. The input voltage range is 0–5 V, therefore a 1 V input to the power supply corresponds to a 4 V output from the power supply. For the current-control mode, the power supply output current is proportional to an input voltage. Again, the input voltage range is 0–5 V, therefore a 1 V input would correspond to a 2 A output from the power supply for a constant load resistance. The output voltage from the dSPACE system is the input voltage to the power supply. In this experiment, the HP power supply is operated in the voltage-control mode.

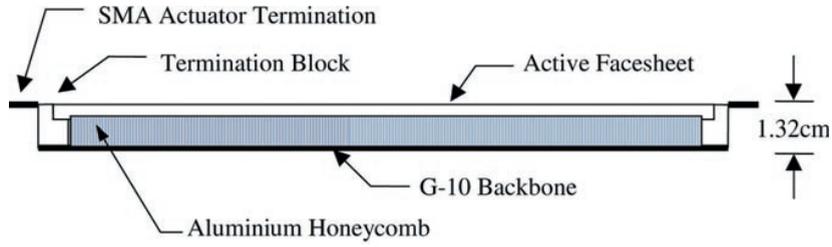


Figure 6. Schematic diagram of a SMA composite beam (side view).

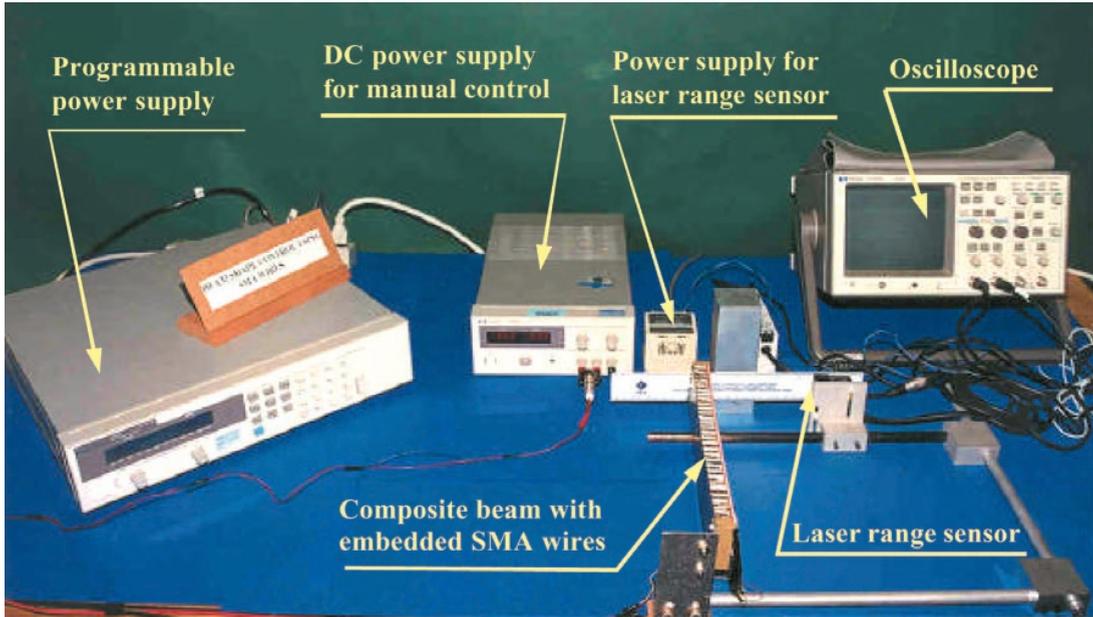


Figure 7. Photograph of the SMA beam experiment.

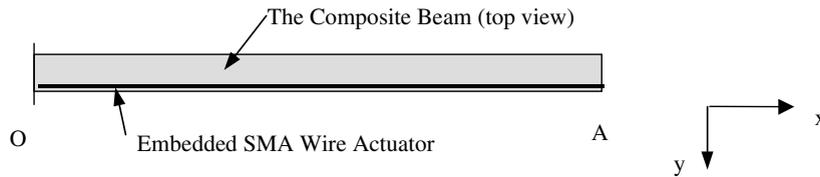


Figure 8. Schematic diagram of the SMA composite beam (top view).

The HP power supply delivers a current proportional to the control voltage to the SMA wires, which heats the wire. The heating of the wire results in a phase transformation and a shrinking of the wire; the beam will be bent and its tip moves. The laser sensor detects this movement. An HP oscilloscope is used to display both the displacement output voltage from the laser sensor and the output voltage from the real-time control system.

3. Control system design

First the coordinate system is defined to assist control design. Figure 8 shows a top view of the SMA composite beam. The end at point O is constrained and the end at point A (the beam tip) is free to move in the y direction. The SMA wires are embedded only in the side face facing $+y$ direction. As current is applied to the SMA wire actuator, the beam

tip will displace only towards the $+y$ direction, and when the current is removed, the beam tip will move in the $-y$ direction, towards its starting position.

We define the following control errors

$$e = y - y^d \quad \dot{e} = \dot{y} - \dot{y}^d \quad (1)$$

where y^d and \dot{y}^d are the desired tip position and velocity, respectively. Since we consider a regulator problem, $\dot{y}^d = 0$. Therefore, $\dot{e} = \dot{y}$. We also define the auxiliary control variables r and \dot{r} as

$$r = \dot{e} + \lambda e \quad \dot{r} = \ddot{e} + \lambda \dot{e} \quad (2)$$

where λ is a positive constant. The controller is proposed as

$$\dot{i} = \dot{i}_f - K_D r - \rho \tanh(ar) \quad (3)$$

where K_D and a are positive constants. The ρ , robust gaining, is an assumed upper bound on the nonlinearities associated

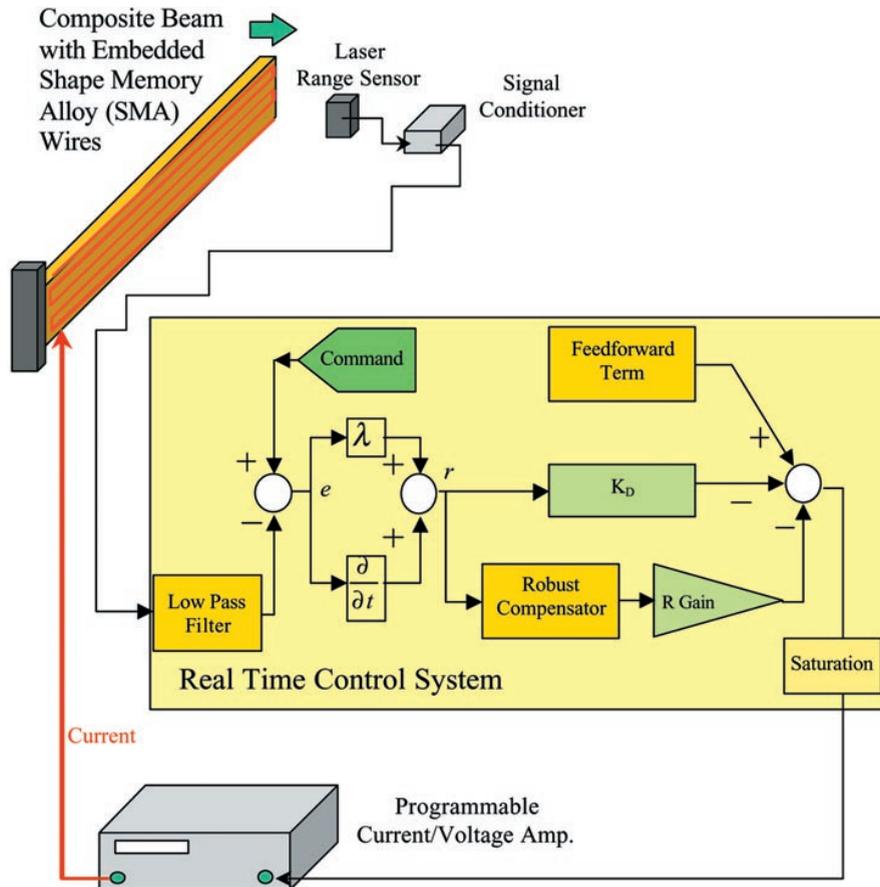


Figure 9. Schematic diagram of the SMA beam control strategy along with the experimental set-up.

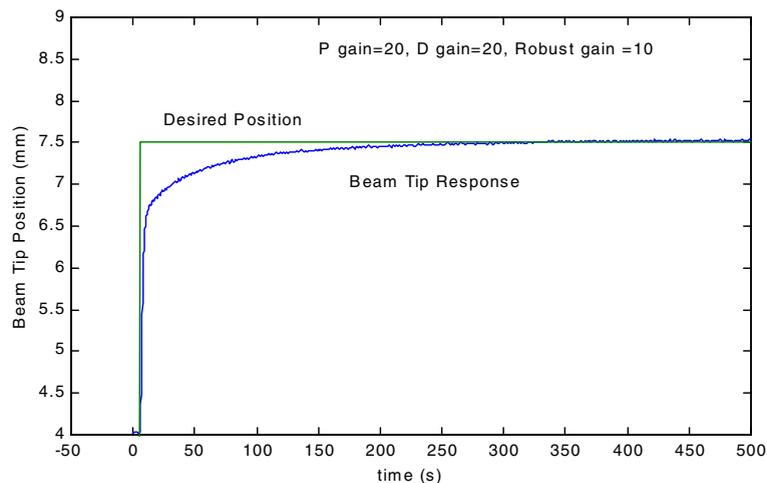


Figure 10. Tip position control of the composite beam with robust compensation.

with SMA wire actuator for the composite beam. The functions of each control action in (3) are discussed as follows.

- The $-K_D r$ is a linear feedback torque functioning as a Proportional plus Derivative (PD) control (Song *et al* 2000). Proportional control is used to decrease the steady-state error and increase the responsiveness of the actuator. The derivative control is to increase damping and to stabilize the actuator.
- The i_f is a feedforward action. This control action is used to supply the SMA actuators with the appropriate amount of current to pre-heat the SMA actuators and compensate for environmental heat losses (Song *et al* 2000).
- The $-\rho \tanh(ar)$ is a robust compensator and is used to compensate for the hysteresis of the actuator and to increase control accuracy and stability.

In this control approach, $r = 0$ functions as the sliding surface, on which the system is asymptotic stable, i.e. the control error is zero. In order to force the system onto the sliding surface we employed the so-called smooth robust controller $-\rho \tanh(ar)$. The robust compensator is continuously differentiable with respect to the control variable r . It generates a smooth control action. Compared with the commonly used bang–bang or saturation robust controllers, the smooth robust controller has advantages in ensuring both a smooth control input and the asymptotic stability of the closed-loop system (Cai and Song 1993, Cai and Abdalla 1993). A detailed comparative study is provided in Song and Mukherjee (1998).

A diagram illustrating the control strategy along with the experimental set-up is shown in figure 9.

4. Experimental results

The controller employing a robust compensator is implemented using Matlab/Simulink and dSPACE real-time interface software. The controller parameters are: $\lambda = 1$, $K_D = 20$, $\rho = 10$, and $a = 10$. The feedforward value is 0.255. During the control, the tip of the beam is required to move from 4 to 7.5 mm. Shown in figure 10 is the time history of the beam tip position when the controller uses the robust compensator. It is clear from the figure that accurate tip position control is achieved. The transient performance is satisfactory and there is no overshoot. As compared to the case without the robust compensator (Song *et al* 2000), the case with the robust compensator has a quicker response. It takes about 75 s to reach 7 mm deflection from 4 mm for the case without a robust compensator (Song *et al* 2000) and only 25 s to move the same amount for the case with a robust compensator, figure 10. This experiment demonstrates the feasibility of using SMA wire actuators for precision position control. The advantage of position control of SMA wire actuators using the robust compensator is also demonstrated.

5. Conclusions

In this paper, a new approach to position control of a SMA wires actuated composite beam is presented. The composite beam is a honeycomb structure with SMA wires embedded in one of its phase sheets for active actuation. The new control approach includes a feedforward action, a PD control

action, and a robust compensator. The robust compensator is designed to compensate the nonlinearity associated with the SMA wire actuators, to improve transient response, and to increase the system's stability. The controller is designed in Matlab/Simulink and implemented in real-time using a dSPACE data acquisition and control system. The experiment was conducted and successfully demonstrated that SMA actuators with the proposed control design can precisely control the tip position of a composite beam. Future work will involve further improving the transient response of the smart composite beam.

Acknowledgments

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