Active Position Control of a Shape Memory Alloy Wire Actuated Composite Beam

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ABSTRACT

This paper presents the design and experiment results of active position control of a shape memory alloy (SMA) wires actuated composite beam. The composite beam is honeycomb structured with shape memory alloy wires embedded in one of its phase sheet for active actuation. The potential applications of this experiment include thermo-distortion compensation for precession space structure, stern shape control for submarines, and flap shape control for aeronautical applications. Shape memory alloy wires are chosen as actuating elements due to their high recovery stress (maybe >700 MPa) and tolerance to high strain (up to 8%). However, shape memory alloy wires are inherently nonlinear and pose a challenge for control design. A robust controller is designed and implemented to active control the tip position of the composite beam. The experiment setup 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. Experiments demonstrated the effectiveness of the robust control.

Keywords: Shape memory alloy, Position control, Robust control, Real-time control, Nonlinearity compensation, Composite beam, SMA wire actuator

1. INTRODUCTION

Shape Memory Alloys (SMA's) are materials which have the ability to return to a predetermined shape when heated. Due to their unique property: a reversible crystalline phase transformation enables a SMA object to recover their original heat-treated shape (up to 8% strain) when heated above a critical transformation temperature or to generate high recovery stresses (>700 MPa is possible), Shape memory alloy is often used as

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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 shape memory alloys results 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 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.

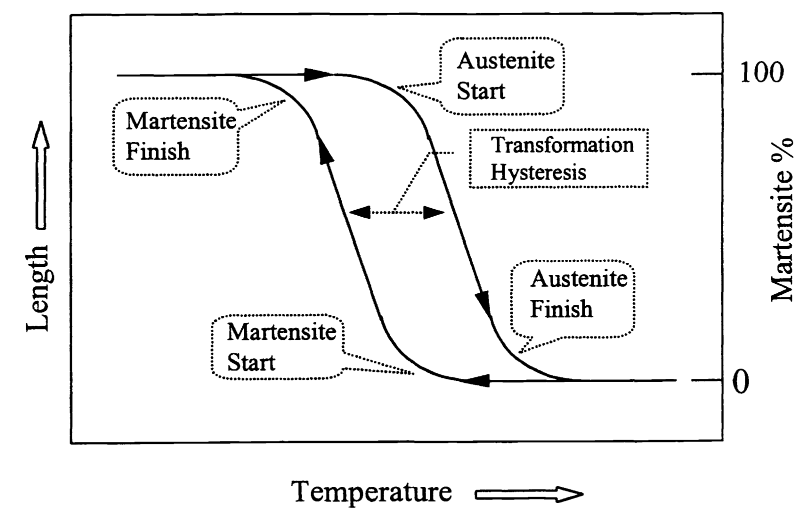

Fig. 1.1 Transformation Hysteresis versus Temperature for a SMA Actuator under Constant Load (stress) as It is Cooled and Heated.

The transformation exhibits a hysteretic effect, in that the transformations on heating and on cooling do not overlap (Fig. 1.1). Thus SMA actuators exhibit hysteresis, a nonlinearity, which adversely affect precision control of the structures activated by SMA actuators. To design control methods to compensate for the nonlinearities associated with SMA actuators 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 facesheet attached to honeycomb core. The composite beam can be deformed by supplying direct current ranging from 1.5 – 3.0 amps to the shape memory alloy wires, and the tip of beam can move up to 1.5cm if the base end is fixed. A new approach employing a robust compensator is used to compensate the nonlinearities associated with this composite beam. Real time code is developed and implemented to control the tip position of the composite beam with the base-end fixed. Experimental results demonstrate the effectiveness of the robust control approach.

2. EXPERIMENTAL SETUP

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 become higher, the need for precision active shape control becomes increasingly important. Also thermal distortion for precision space structures must be compensated. To meet these challenges, "smart structures" employing shape memory alloy actuators are being researched.

Shown in Fig.2.1 is a smart composite space antenna with active shape control using SMA wire actuators. SMA wire actuators are embedded into both surface of the composite antenna. Due to adverse effects, such as thermal distortion, the surface shape of the antenna may be deviated from its desired shape. To correct this error, a calculated current is sent to the appropriate SMA wire actuator to ensure 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 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 (Fig.2.2). To be able to precisely control the trailing edge flap position is the central idea to reduce rotorcraft vibration due to aerodynamic loading.

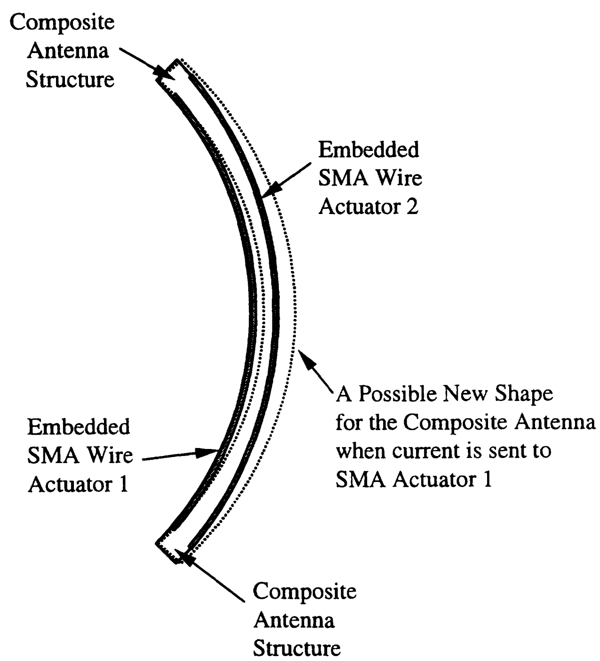

Fig. 2.1 A Smart Space Antenna with Active Shape Control using Embedded SMA Wire Actuators

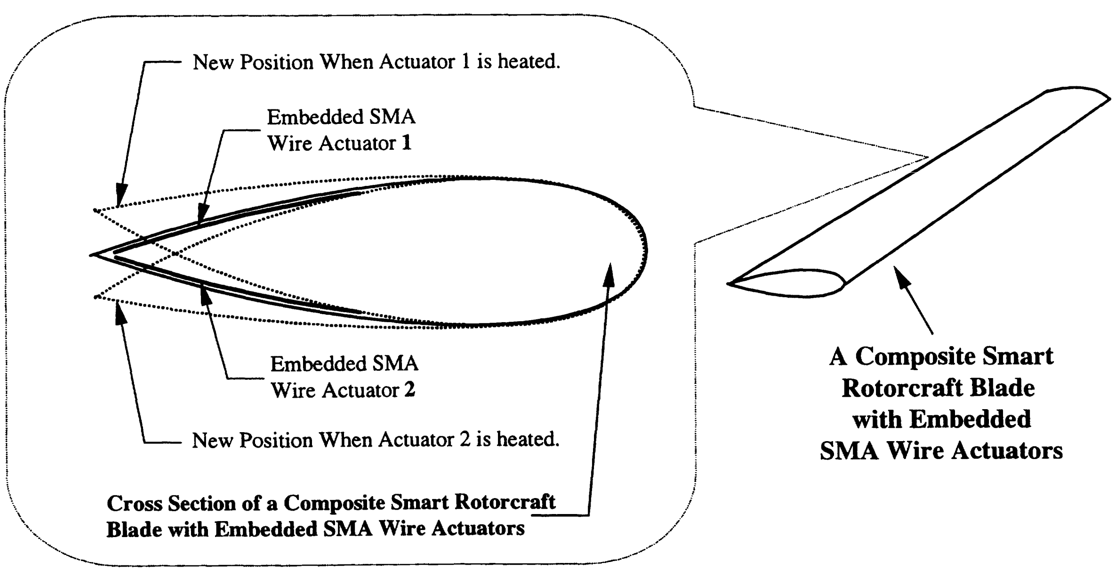

Fig.2.2 Vibration Reduction in Rotorcraft using Actively Controlled Trailing Edge Flaps

The motivation for the experimental setup is to have a test bed to demonstrate the concept of using SMA as actuators for aerospace related applications and to develop advanced method to control the SMA actuators.

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 is developed, as shown in Fig.2.3. When heated, the shape memory wire actuators can deform the composite structure. For simplicity, SMA wire actuators are only embedded in one side of the composite beam. A composite beam is used because of its light weight and the convenience to embed actuators. Shape memory alloy wires are chosen as actuating elements due to their high recovery stress (maybe >700 MPa) and tolerance to high strain (up to 8%).

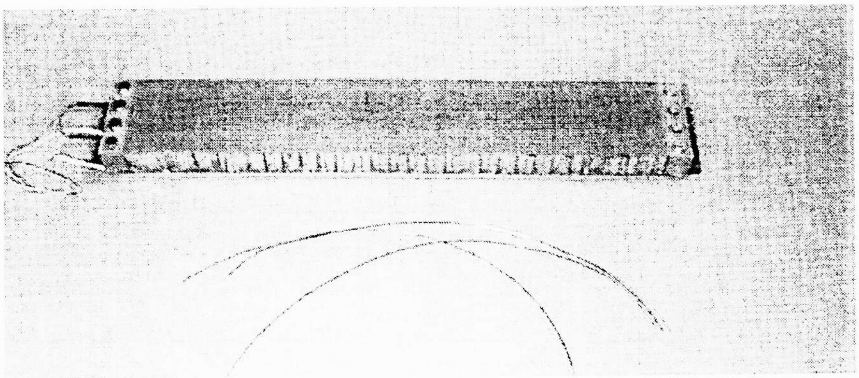

Fig.2.3 The composite beam with embedded SMA wire actuators and some SMA wires

The overall dimensions of the beam are 30.48 cm long, 5.08 cm wide and 1.32 cm thick. Fig.2.4 provides a top view of the beam. Fig.2.5 presents a side view of the beam. The beam is constructed of a 1.27 cm thick 5052 aluminum honeycomb core, with a 0.81 mm thick G-10 backbone, a 2.54 mm thick Conathane® urethane casting system UC-49 compliant facesheet, and two ultem 2300 termination blocks. SMA wires are embedded within a low modulus elastomeric facesheet attached to honeycomb core. The opposing side of the beam consists of a high modulus glass epoxy bonded to honeycomb core. The elasticity of the beam provides the restoring force. There are sixteen 0.381 mm diameter, 30.48 cm, nickel-titanium shape memory wires (two sets of eight wires electrically wired in parallel) embedded in the compliant facesheet. The corresponding circuit resistance of the wires is 10.3 ohms [Kelly, 1998].

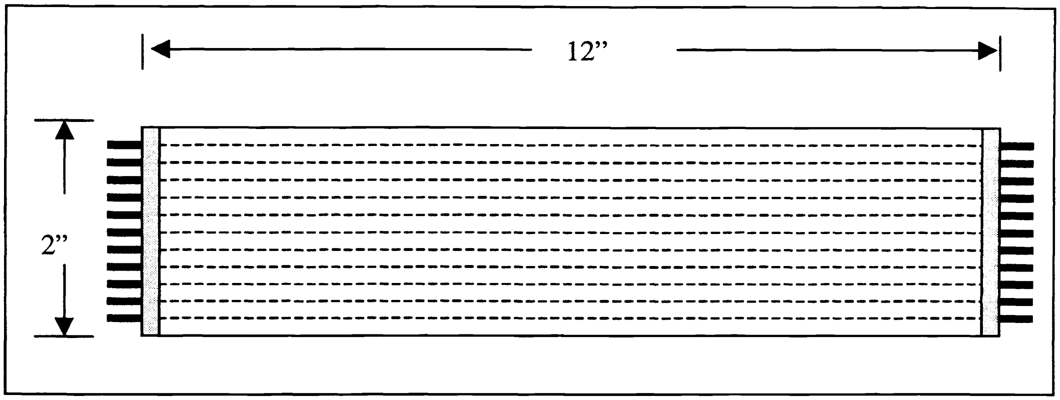

Fig.2.4 Shape memory composite beam (top view)

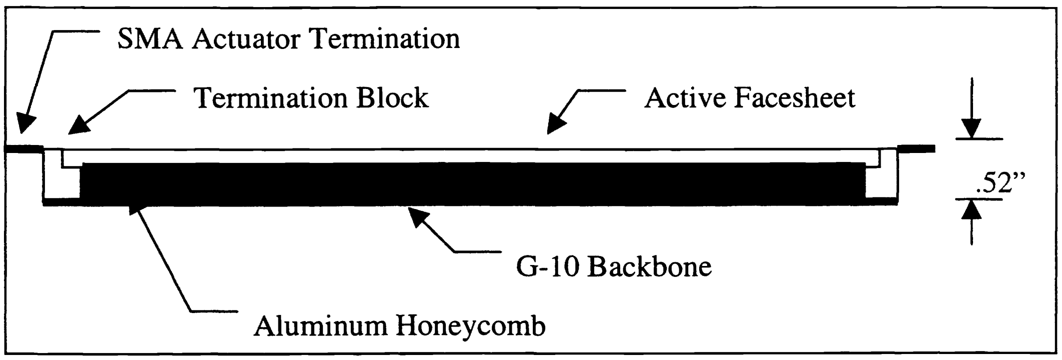

Fig.2.5 Shape memory composite beam (side view)

The shape memory composite beam can be activated by supplying current ranging from 1.5 – 3.0 amps to the shape memory alloy wires. The exact amount of current depends on the desired response time and degree of actuation. Current in excess of 3 amps or extended hold times at maximum deflection can result in degradation of the urethane facesheet.

2.3. Overall Experimental Setup

The purpose of the experiment is to actively control the tip motion of the composite beam actuated by SMA wire actuators. A diagram of the overall composite beam experiment is shown in Fig.2.6. Major components of this experiment includes an HP programmable power supply (model 6542A), an HP low voltage power supply, the composite beam, an NAIS laser analog sensor (model LM100), an HP oscilloscope, and a PC (not shown in Fig.2.6) loaded with Matlab/Simulink, and a dSPACE data acquisition and real time control system (not shown in Fig.2.6). The dSPACE system employs a Texas Instrument C-30 DSP.

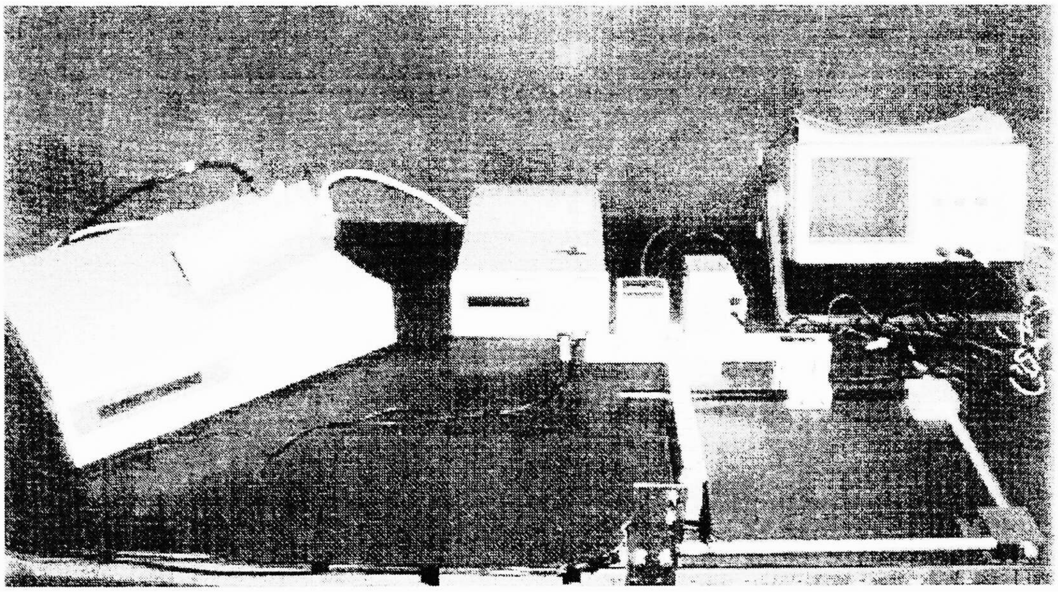

Fig.2.6 The SMA beam experiment

As shown in Fig.2.6, 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 analog 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 VDC. 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 dSPACE system will be amplified by the HP programmable power supply (model 6542A) and then sent to the shape memory alloy wire actuator to activate the composite beam. The power supply has a range of 0 – 20 volts, or 0 – 10 amps. It 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 volts, therefore a 1 volt input to the power supply corresponds to 4 volt 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 volts, therefore a 1 volt input would correspond to a 2 amp output from the power supply for a constant load resistance. The output voltage from dSPACE system is the input voltage to the power supply. In this experiment, the HP power supply is operated in voltage control mode.

The HP power supply then delivers a current proportional to the control voltage to the shape memory alloy wires, and heats the wire. The heating of the wire results in a phase transformation, a shrinking of the wire, and 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. Fig.3.1 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.

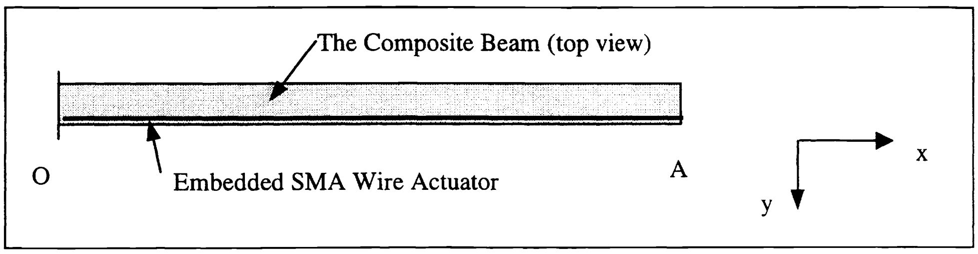

Fig.3.1 SMA composite beam (top view)

We define the following control errors

$$e = y - y^{d}, \; \dot{e} = \dot{y} - \dot{y}^{d} \tag{1}$$

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, $\dot{e} = \dot{y}$.

Also define auxiliary control variables r and $\dot{r}$ by

$$r = \dot{e} + \lambda e, \; \dot{r} = \ddot{e} + \lambda \dot{e} \tag{2}$$

where λ is a positive constant.

The controller is proposed as

$$i = i_{\mathrm{f}} - \mathrm{K_D}\, r - \rho \,\mathrm{Tanh}(a\, r) \tag{3}$$

where K_D and a are positive constants. The ρ is an assumed upper bound on the nonlinearities associated with SMA wire actuator for the composite beam. In this paper, ρ is also called robust gain. The functions of each control action in Eq.(3) is discussed as follows.

- The $-K_D r$ is a linear feedback torque functioning as a Proportional plus Derivative (PD) control. Proportional control is used to decrease steady-state error and increase 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 actuator with the appropriate amount of current to compensate for environmental heat losses.
- The $-\rho \mathrm{Tanh}(a\,r)$ 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 $-\rho \mathrm{Tanh}(a\,r)$. 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 smooth control input and 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 (1997).

A diagram illustrating the control strategy along with the experimental setup is shown in Fig.4.1.

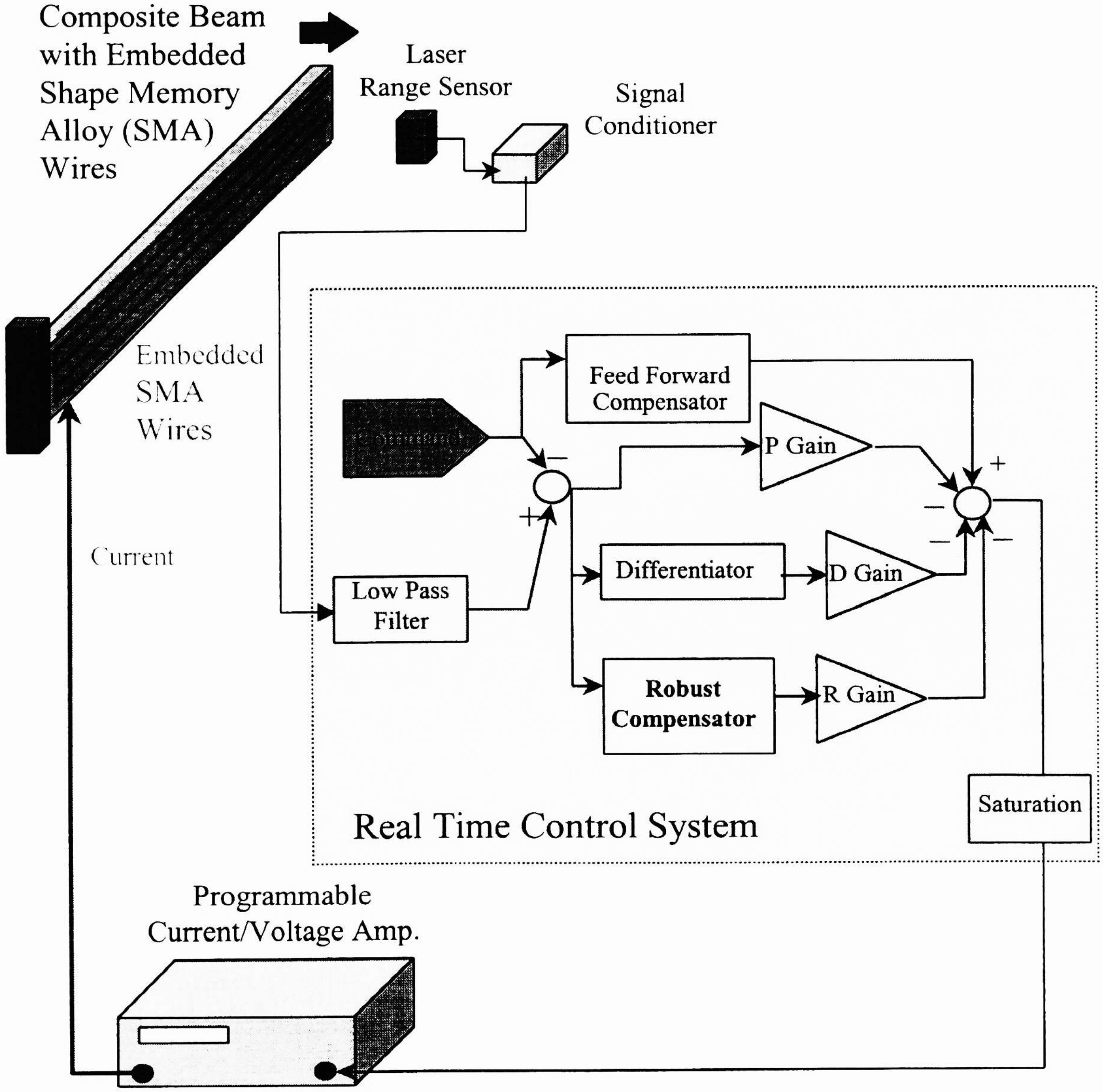

Fig.3.2. SMA beam control strategy along with the experimental setup

4. EXPERIMENTAL RESULTS

The controller employing a robust compensator is implemented using Matlat/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 .255. During the control, the tip of the beam is required to move from 4mm to 7.5mm. Shown in Fig.4.1 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 overshot. This experiment demonstrates the feasibility of using SMA wire actuators for precision position control. The advantage of position control of SMA wire actuators using robust compensator is also demonstrated.

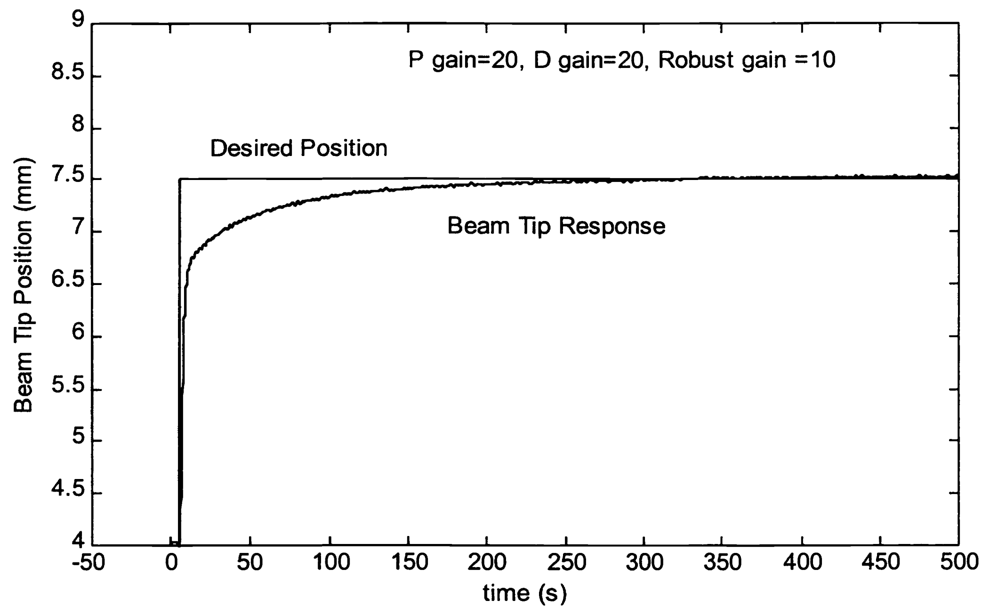

Fig.4.1 Tip position control of the composite beam with robust compensation.

5. CONCLUSION

In this paper, a new approach to position control of a shape memory alloy (SMA) wires actuated composite beam is presented. The composite beam is honeycomb structured with shape memory alloy wires embedded in one of its phase sheet for active actuation. The new control approach includes a feedforward action, a PD control action, and a robust compensator. The robust compensator is design to compensate the nonlinearities associated with the SMA wire actuators. The controller is designed in Matlab/Simulink and implemented in real-time using a dSPACE data acquisition and control system. Experiment was conducted and successfully demonstrated that shape memory alloy actuators with the proposed control design can precisely control the tip position of a composite beam.

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